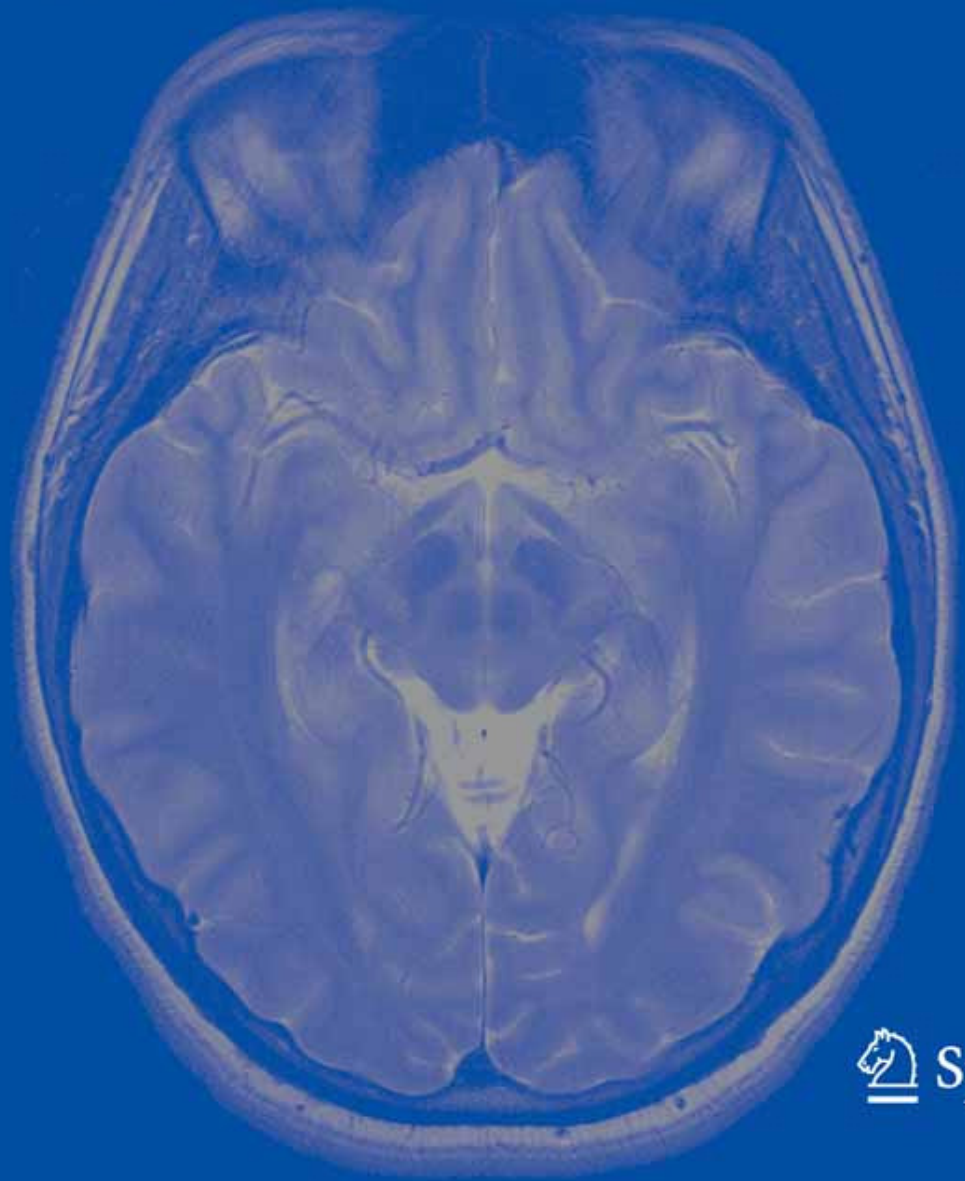
T. Scarabino · U. Salvolini
in collaboration with
F. Di Salle · H. Duvernoy · P. Rabischong

Atlas of Morphology and Functional Anatomy of the Brain



Springer

T. SCARABINO · U. SALVOLINI
in collaboration with
F. DI SALLE · H. DUVERNOY · P. RABISCHONG

ATLAS OF MORPHOLOGY AND FUNCTIONAL ANATOMY OF THE BRAIN

With 166 Figures

Springer

T. Scarabino, S. Giovanni Rotondo, Italy

U. Salvolini, Ancona, Italy

F. Di Salle, Pisa, Italy

H. Duvernoy, Besançon, France

P. Rabischong, Montpellier, France

This edition of **Atlas of morphology and functional anatomy of the brain** by **Scarabino – Salvolini – Di Salle – Rabischong – Duvernoy** is published by arrangement with Idelson-Gnocchi srl, Naples, Italy

© 2003 Gruppo Editoriale IDELSON-GNOCCHI srl dal 1908

ISBN-10 3-540-29628-X Springer Berlin Heidelberg New York
ISBN-13 978-3-540-29628-7 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2005934100

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media
http://www.springeronline.com

© Springer Berlin Heidelberg 2006

Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Product liability: The publishers cannot guarantee the accuracy of any information about the application of operative techniques and medications contained in this book. In every individual case the user must check such information by consulting the relevant literature.

Editor: Dr. Ute Heilmann
Desk Editor: Meike Stoeck
Production Editor: Joachim W. Schmidt
Cover Design: eStudio Calamar, Spain

Typesetting: FotoSatz Pfeifer GmbH, 82166 Gräfelfing, Germany
Printed on acid-free paper – 24/3151 – 5 4 3 2 1 0

CONTRIBUTORS

M. Armillotta, Rotondo
A. Bertolino, Bari
G. Blasi, Bari
S. Cirillo, Napoli
R. Elefante, Napoli
F. Esposito, Napoli
P. Ghedin, Milano
G.M. Giannatempo, S. Giovanni Rotondo
V. Latorre, Bari
M. Nardini, Bari
F. Nemore, S. Giovanni Rotondo
G. Polonara, Ancona
T. Popolizio, S. Giovanni Rotondo
T. Salvolini, Ancona
A. Scranieri, S. Giovanni Rotondo
E. Seifritz, Basel
A. Simeone, S. Giovanni Rotondo
A. Volpicelli, Napoli

CONTENTS

Preface IX

Introduction – Comprehensive Anatomy of the Human Brain 1

MORPHOLOGY ATLAS 21
Surface Images 23
Axial Cuts 35
Coronal Cuts 61
Sagittal Cuts 85

FUNCTIONAL ATLAS 107

PREFACE

The recent advances in neuroimaging techniques, particularly magnetic resonance (MR), have greatly improved our knowledge of brain anatomy and related brain function. Morphological and functional investigations of the brain using high-definition MR have made detailed study of the brain possible and provided new data on anatomo-functional correlations. These studies have fuelled the interest in central nervous system imaging by clinicians (neuroradiologists, neurosurgeons, neurologists, neurophysiologists, and psychiatrists) as well as biophysicists and bioengineers, who are at work on new and ever more sophisticated acquisition and processing techniques to continue to improve the potential of brain imaging methods.

The possibility of obtaining high-definition MR images using a 3.0-T magnet prompted us, despite the broad existing literature, to conceive an atlas illustrating in a simple and effective way the anatomy of the brain and correlated functions.

Following an introductory chapter by Prof. Pierre Rabischong, the atlas is divided into a morphological and a functional imaging section.

The morphological atlas includes 3D surface images, axial, coronal, and sagittal scans acquired with high-definition T2 fast spin echo (FSE) sequences, and standard and inverted-contrast images. The MR scans are shown side by side with the corresponding anatomical brain sections, provided by Prof. Henri Duvernoy, for more effective comparison. The anatomical nomenclature adopted for both the MR and the anatomical images is listed in an jacket flap for easier consultation.

The functional atlas, edited by Prof. Francesco Di Salle, presents MR images of the cortical activation of the main functional areas of the brain (auditory, motor, visual, language, somatosensory, etc).

The atlas is principally directed at radiologists and neuroradiologists for use in their daily practice to sustain increasingly accurate diagnoses, but also at neurosurgeons, neurologists, and all those who are interested in this fascinating subject.

We hope that this book may also become a reference and teaching tool in medical and postgraduate schools of radiology, neurosurgery, neurology, and psychiatry, both to make the students familiar with a non-invasive diagnostic method such as MR and to enable them to learn in a simple, effective, and practical way the topographic and functional anatomy of the complex structure of the human brain.

This book would never have been realized without the work of several experts, to whom we are deeply indebted. In particular, we gratefully acknowledge the contribution of Professors Rabischong and Duvernoy, neuroanatomical scholars of world renown.

Ugo Salvolini *Tommaso Scarabino*

Recommended Reading

Cabanis EA, Chevrot A, Cosnard G, et al. Radioanatomie en coupes TDM - IRM. Pradel, Paris 1989.
Cabanis EA, Doyon D. Atlas d'IRM de l'encephale et de la moelle: aspects normaux. Masson, Paris 1987.
Duvernoy H. The Human Brain stem and Cerebellum, Springer Verlag. New York Wien 1995.
Duvernoy H. The Human Brain: surface, blood supply and three-dimensional sectional anatomy. 2nd ed. Springer Verlag, New York-Wien 1999.
Hanaway J, Woolsey TA, Gado MH Roberts Jr MP. Il sistema nervoso centrale dell'uomo. Atlante. Edi-Ermes, Milano 2000.
Leblanc A. Encephalo-peripheral nervous System. Springer, Berlin/Heidelberg/New York 2001.
Madden ME. Introduction to sectional anatomy. Lippincott W&W, Philadelphia/Baltimore 2001.
Rabischong P. Le programme Homme. Presses Universitaires de France, Paris 2003.
Salamon G. Huang YP. Radiologie anatomy of the brain. Springer-Verlag, Berlin/Heidelberg/New York 1976.
Tamraz JC. Comari YG. Atlas of regional anatomy of the brain using MRI with functional correlations, Springer-Verlag editore, Berlin/Heidelberg 2000.

INTRODUCTION

COMPREHENSIVE ANATOMY OF THE HUMAN BRAIN

The comprehensive approach of anatomy is based on the identification of the technical problems related to the performance of functions. Therefore we have the solution and not the problem, as man was not built by man. To go from function to morphology is to follow an inverse process that permits to understand the anatomical solution through the problems, thus validating it. In other words, starting from the assumption that the constructor of the human machine did not make technical mistakes, answers as to the "how" and "why" must be provided for every organ and function. As regards the nervous system, it is particularly true that the technical organisation seen and described on anatomical and radiological images responds to a logical and intelligent construction plan and not to a fuzzy and hazardous self-organisation. In order to read brain images, with their present rich diversity – thanks mainly to the progress of imaging techniques –, it seems to be necessary not only to memorise a large number of anatomical details, but also, and first of all, to understand the general "spirit" of the brain's construction.

The brain is a whole, covering many different functional aspects related to particular mind specifications, organs and command and control systems. This unthinkable complexity is in apparent contrast to the general ignorance of the driver of the human machine with regard to its "biohardware" and software. Even though the human species is the sole capable of understanding biology, the level of knowledge required for functioning is very low. Therefore, logically, two levels of neural control can be identified: the decisional level, expressed in a global, simple and functional language (thinking, reading, writing, walking, grasping, jumping…), and the execution level unconsciously managing all the inputs and outputs according to a heterarchical organisation in which different neural centres are interactively linked. Roughly 80% of the brain's circuitry is devoted to the execution level, which explains the complexity of its internal organisation. Before exploring the different neural systems of the brain, which can be subsumed under the four main functions described below, it is interesting to analyse briefly the original technical solutions of the brain's construction.

1. THE ORIGINAL TECHNICAL SOLUTIONS OF THE BRAIN'S CONSTRUCTION

The central nervous system is a very large interactive processor capable of processing a great variety of sensory inputs, of storing information for short or long periods, and of expressing the mental output by language, mimicry or behaviour.

1.1. The discontinuous neuronal network

Based on the structure of the neurons, where dendrites receive information and axons carry it outside, the neuron-to-neuron synaptic junction is one of the most original characteristics of the nervous system. The histological organisation of synapses characterises a selective gate filtering the information flow. The appropriate key is of biochemical nature and consists of all the neurotransmitters identified to date. Their great variety explains all the inhibition

and facilitation processes that allow the brain to perform complex tasks. In fact, neurosecretion is closely connected with the depolarisation waves conducting excitation along the nerves and enabling the amazing performances of the brain processor in a relatively small volume. The effectiveness of all drug therapy is also related to this biochemical management of signal processing.

At the level of the cortex, the billion neurons are interconnected in a horizontal and vertical matrix with six layers that form during foetal growth according to a very precise procedure. All the neuroblasts are initially concentrated around the ventricular cavities, whence they migrate towards the outer part of the brain, each neuroblast ascending along a radial glial fibre to find its

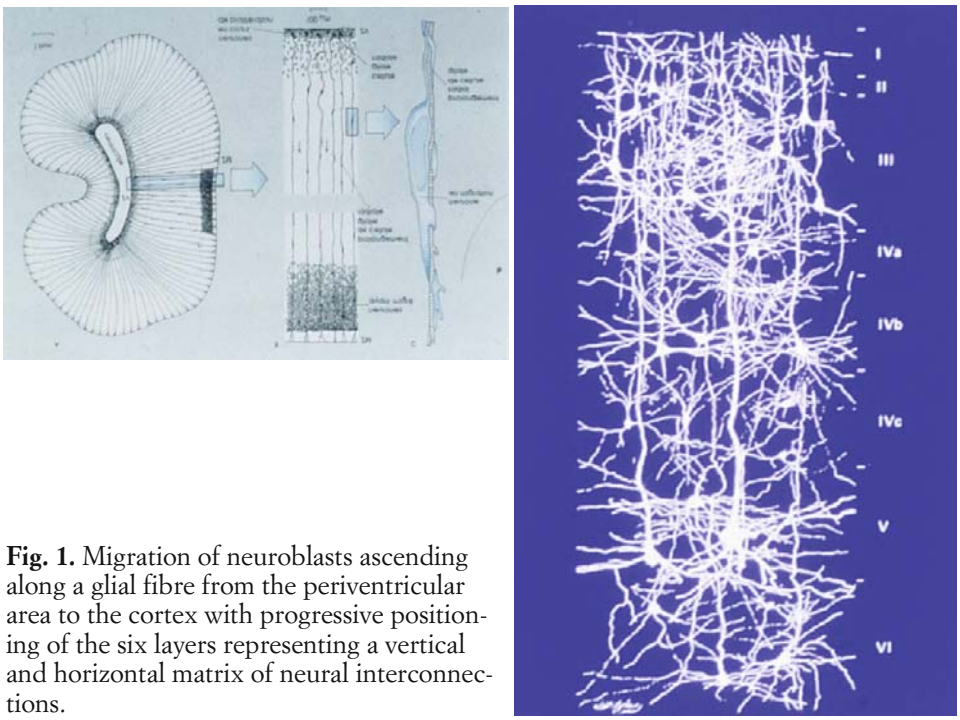


Fig. 1. Migration of neuroblasts ascending along a glial fibre from the periventricular area to the cortex with progressive positioning of the six layers representing a vertical and horizontal matrix of neural interconnections.

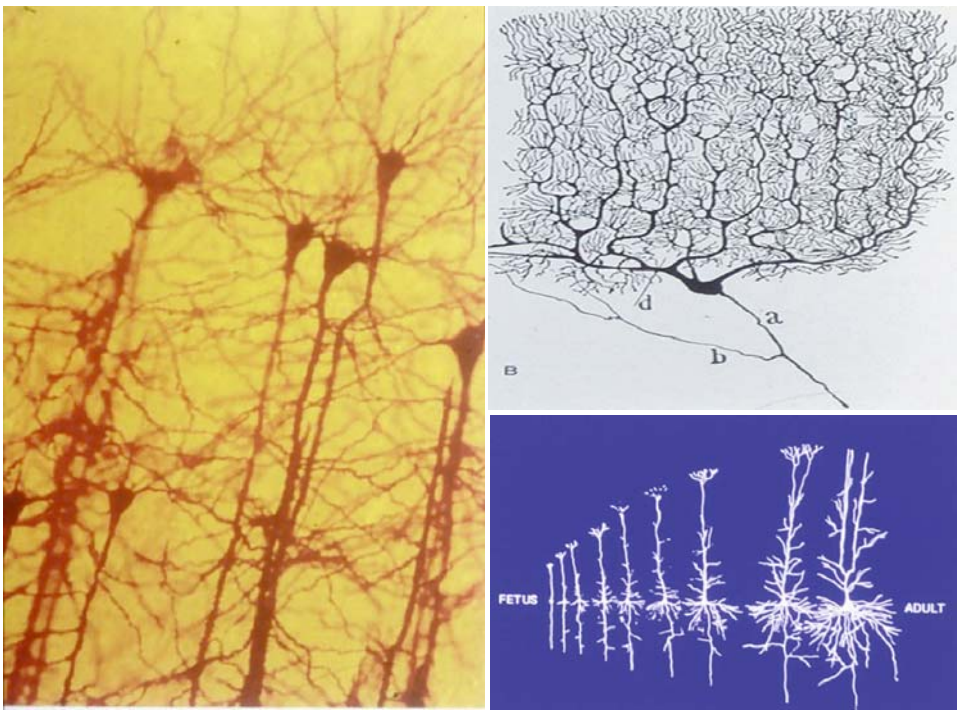


Fig. 2. Neurons do not reproduce but are very well preserved by glial cells

correct location in the stratified matrix (figure 1). The most superficial layer is the last to be fixed and it seems obvious that a full set of genetic instructions is needed to guide this amazing construction without mistakes. All the maintenance services (metabolic exchanges with blood, depuration, immunological defence), as well as the production of the myelin sheath isolating the nervous fibres and providing mechanical resistance, are ensured by glial cells: astrocytes and oligodendrocytes (figure 2). Cabling the different axons and dendrites, which in some nerves exceed 1 m in length and have a maximum diameter of 25 µ, is an incredible challenge that takes time. Myelination of nerves and central pathways is not complete at birth.

As mentioned above, the driver of this complex machine is largely unaware of it all, and requires the system to be pre-programmed and pre-cabled. The general type of control is heterarchical, involving an interactive level-to-level organisation in both directions from top to bottom and vice versa. This emphasises the functional importance of feedback and feedforward mechanisms, which are among the main components of the automatisms, closed-loop regulations and servomechanisms that are found in the unconscious execution area of the brain. The obligatorily simple interface of command used by a driver operating with simple orders masks the complexity of the nervous circuits and centres.

1.2. The adaptable blood brain supply

As demonstrated by the high-pressure injections of black ink performed by Henri Duvernoy on fresh human brains (figure 3), the vascular network of the brain is particularly dense and the concentration of vessels is closely related to the density of neurons. This allows to identify nuclei and cortical structures simply by looking at the angio-architecture. Another important technical feature is the economical approach by which the brain feeds the operating neural centres more than those at rest. This is managed by astrocytes, which are directly connected with the neurons. fMRI is based on this principle (BOLD), whereby the detection of the signal from desoxyhaemoglobin of venous blood allows to visualise the active areas of the cortex during the performance of a particular task. The absence of anastomotic vessels before cortical distribution, which generates a terminal type of blood supply, explains the severity of the anoxic lesions due to vascular occlusion and the irreversibility of the connected neural deficits despite the possibility of some compensation by virtue of the redundancy of the circuits.

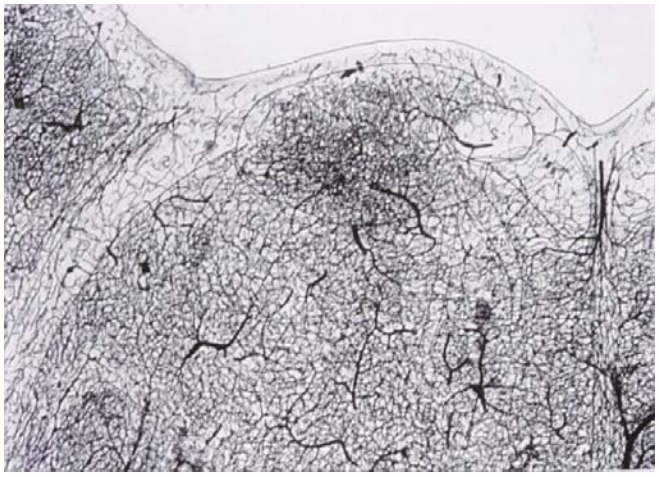


Fig. 3. Microvascularisation (H. Duvernoy)

The richness of the vascular network, which pulsates like a vascular sponge at each systolic cardiac beat, justifies a protection system against overpulsation of the blood flow, as in the case of muscular effort or exercise. Thus, the internal carotid artery, which feeds most of the cortex, is endowed with two interesting anatomical structures presumably, in relation to this technical problem. The first is the rigid petrous canal in which the artery runs. This 2.5 cm osseous canal slows down the waves generated by the systolic beats when the heart is pulsating faster, preventing the building up of dangerous overpressure in the crowded capillary brain network. The second is the double S formed by the artery in the cavernous sinus, which we have interpreted as a pump preventing stagnation of the venous blood coming from the ophthalmic veins, given that the retina does not tolerate dramatic slow-downs of the blood flow. This cavernous pump also has the role of controlling blood temperature in the internal carotid artery, preventing the risk of brain hyperthermia thanks to the considerable amount of sinus venous blood from the nasal mucosa, which is normally refrigerated by the air flow in the nasal cavity. A similar process is found in many animals having a rete mirabilis around the carotid artery at the base of the skull. In addition, the two vertebral arteries are the best protected arteries in the body. They run from C6 in the cervical vertebral canal on the lateral side of the vertebrae. The critical part is the crossing of the craniocervical C1/C2 cardan, where the horizontal rotation of C1 around the odontoid process of C2, in addition to the extension of the head, produces an elongation and compression of one vertebral artery, dramatically reducing the blood flow. The technical solution is the unique convergent anastomosis of the basilar trunk, which guarantees permanent blood flow to the brain stem, where the vital command centres of breathing are located. The very rich anastomotic circle joining the two carotid arteries and the basilar trunk at the base of the brain constitutes a safe system ensuring the blood supply to the brain in any mechanical hydraulic condition in relation to the different positions of the head.

1.3. The selective filtration of sensory inputs

Most sensory organs, like the ear and nose, are plug-in all day long. However, the memory zones located in the different specific areas of the brain cannot store all this information without risking saturation. The hippocampus (figure 4), located in the medial part of the temporal lobe, acts as a filter, memorising for a short period of time some events of daily life, like the colour of the eyes of the bus driver, which are then rapidly forgotten. In any case, the hippocampus is integrated in a very large system, the limbic system, where Papez described the emotions circuit. Therefore, long-term memory is closely linked with the emotions, explaining why our oldest memories are always related to emotional events. Attention – also a function activating different areas of the cortex – is capable of interfering with the quality and duration of memories. Unlike a computer, the brain can also completely lose information. Anyway, the driver is totally unaware of the process of recalling information from the memory areas, reinforcing the designation of “black box” attributed to mental speculation. Another specific filter is the thalamus, which receives all the sensory inputs except for the olfactory signals, which go directly to the amygdala complex. Pain signals have priority, which allows them to inundate the cortex. A first important filtration structure of nociceptive inputs is located within the substantia gelatinosa of the posterior horn of the spinal cord, where competition between the signals from the large fibres and those from the small C fibres underpins the gate control theory of Melzack and Wall.

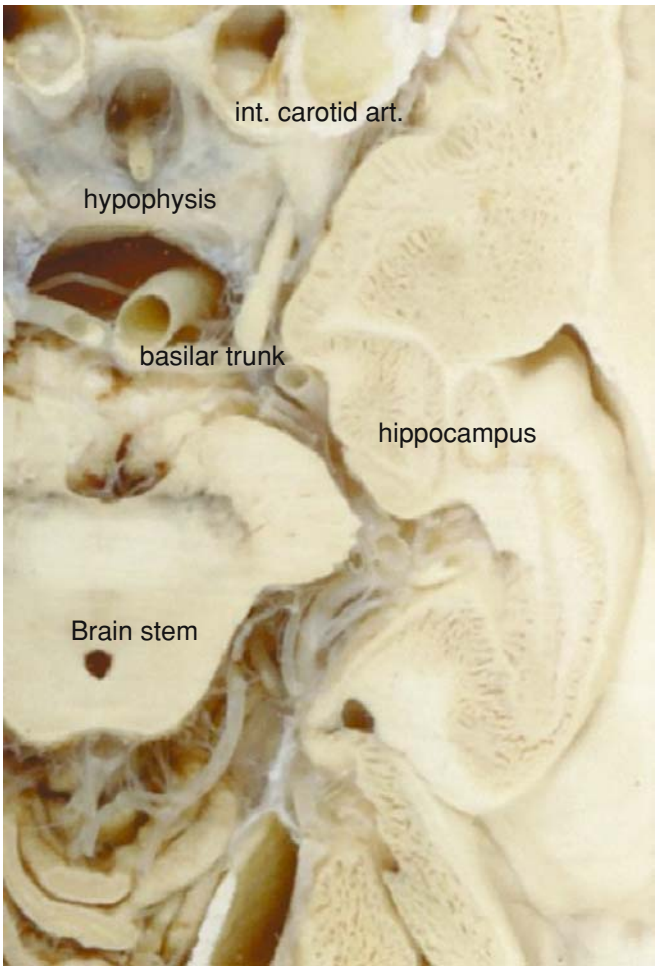


Fig. 4. Right horizontal section.
The hippocampus is an important neural centre that filters sensory inputs and stores them on short and long term memory. It plays a prominent part in the Papez circuit belonging to the limbic system which is the preprogrammed generator of survival behaviour.

1.4. The full automatism of biological maintenance

Given the inability of the driver of the human machine to control consciously all the complex biological maintenance operations, like non-stop breathing, cardiovascular regulation, endocrine gland management as well as sleep induction, hunger and thirst, body temperature and the vegetative emotional accompaniment, the key word of the neural organisation is automation. The action mode is neural or biochemical by all forms of neurotransmitters, neuromodulators and neurohormones. The management centre is in the hypothalamus, which has a dense concentration of powerful groups of neurons in a very small volume, roughly 4 g compared with the 1400 g of the whole brain.

The hypothalamus is divided into two main parts: medial with an anterior, a medial and a posterior group of nuclei, and lateral. More simply, three regions can be identified: chiasmatic or preoptic, tuberal and mamillary. In addition, some groups of ependymal cells endowed with a rich blood supply, called circumventricular organs, can be isolated, including subfornical organ and pineal gland which, unlike the other brain structures, have no blood barrier. This explains their role in the direct secretion of the neurohormones acting on the regulation of the endocrine system: first the posthypophyseal hormones oxytocin and vasopressin, and second the releasing hormones stimulating the secretion of the anterior part of the hypophysis: corticotropin-releasing factor (CRF) from the paraventricular nucleus, prolactin-releasing hormone, growth hormone releasing hormone (GH RH), growth hormone-inhibiting hormone (GH IH), i.e. somatostatin (SST), thyreostimulin-releasing hormone (TRH), and luteinising hormone-

releasing hormone (LH RH), and gonadotropin-releasing hormone (GnRH), acting on the testes and ovaries. Overall, there are five hypothalamic neuropeptides controlling the adenohypophysis. In addition, some neuropeptides are shared by hypothalamus and adenohypophysis: endorphins (beta-endorphins, enkephalins and dynorphins), which are specifically neuromodulators, particularly for nociceptive inputs. The monoamines are also important in the functions of the endocrine hypothalamus: they are dopamine, serotonin and noradrenalin, acting on different sites of the brain stem.

Perception of the circadian cycle, which is a time controller similar to a clock, is provided by the alternation of day and night perceived by the suprachiasmatic nucleus, which is connected with the retina and inhibits the secretion of melatonin by the pineal gland via a very long route through paraventricular nucleus, brain stem, tractus intermediolateralis of the dorsal spinal cord, with a connection to the superior cervical ganglion of the sympathetic chain, and finally the pineal gland. This particular connection with the vegetative system can explain the cyclical changes in the regulation of the visceral organs, like the heart, in relation to the time of day or night. Many cardiac patients die early in the morning due to the inversion of the cycle of the sympathetic and parasympathetic systems. Melatonin is produced by the pineal gland from serotonin and plays an important role in the inhibition of the endocrine functions of the hypophysis and hypothalamus, particularly the sexual functions, and also has an antioxidant action.

The hypothalamus is also involved in body temperature regulation and hunger and thirst control by way of the lateral hypothalamus, sensitive to blood glucose levels, with special reference to fat tissue proportion in relation to body weight. Therefore, the body weight profile of each individual is recorded in the hypothalamus, even though this does not always prevent anorexia or bulimia. The paraventricular nucleus seems to be the key structure for the integration of these endocrine and vegetative functions.

Another important role of the hypothalamus stems from its participation in the limbic system, which manages the emotions and character. Two areas can be isolated: the posterior and lateral hypothalamus (ergotropic triangle), responsible for aggressiveness, and the lateral hypothalamus, the centre of the somatic expressions of the emotions, which is in relation to the septal area anteriorly and the mesencephalon posteriorly. Finally, the automatic management of biological maintenance is provided for by a large series of centres located in the brain stem and supervised by the hypothalamus, which is also in charge of the endocrine regulation of a large part of the activity of the hypophysis.

The vagal nerve (X), very rich in preganglionic parasympathetic fibres, is the final vector of visceral regulation together with the sympathetic chain. Although the unknowing driver can address the warning dysfunction signals, interference with these well-adjusted automatisms might result in the arising of a new kind of psychosomatic pathology.

1.5. Protection of nerve structures

The encephalon is enclosed in a bony box (figure 5), the neurocranium, made up of two parts: the skull base and the vault. The posterior part of the skull base is organised in the same way as the spine, with the induction of the cord generating the clivus. The anterior part is angled in a kyphotic manner in man and is related to the visceral portion of the face and to the olfactory system. It is interesting to note that the splanchnocranium is generated by the visceral arches, which have skeleton, vessels and specific mixed nerves. The first arch is responsible for the formation of the whole face, with three planes corresponding to the three branches of the trigeminal nerve (V). The second forms the hyoid bone, it is controlled by the facial nerve (VII), and converges on the first arch in the ear. The third arch gives rise to the upper part of the laryngeal cartilage in relation to the glossopharyngeal nerve (IX). The fourth arch forms the lower part of the larynx with the vagal nerve (X+XI), which ends as a cranial nerve at the level of the larynx together with the inferior laryngeal nerve and reaches the furthest part of the intestinal canal as a parasympathetic vector. An ambiguous terminology has been introduced by the anatomists for the accessory nerve (XI). In fact, there are two different nervous entities: the accessory, going to the trapezius and sternocleidomastoid muscles, which is a cervical nerve and not a cranial nerve, originating from the first four cervical spinal segments, and the other portion, which is the motor root of the vagal nerve, corresponding to the recurrent motor nerve of the larynx.

The vault follows the expansion of the telencephalon, which must be considered as the motor of its growth. In the foetus, the brain is smooth, the only depression being the future Sylvian valley (lateral sulcus). Later on, due to the tangential cortical growth of the hemispheres, the primitive skull capsule, initially merely fibrous but progressively becoming covered by converging bony plates giving rise to the suture lines, becomes less and less plastic (figure 6). This is why the cortex is folded, exhibiting gyri that are variable but morphologically discrete in all individuals due to reproducible mechanical fixation structures, like the insula applied on the claustrum and the putamen of the lenticular nucleus. In addition, during their growth the two telencephalic vesicles follow a rotatory

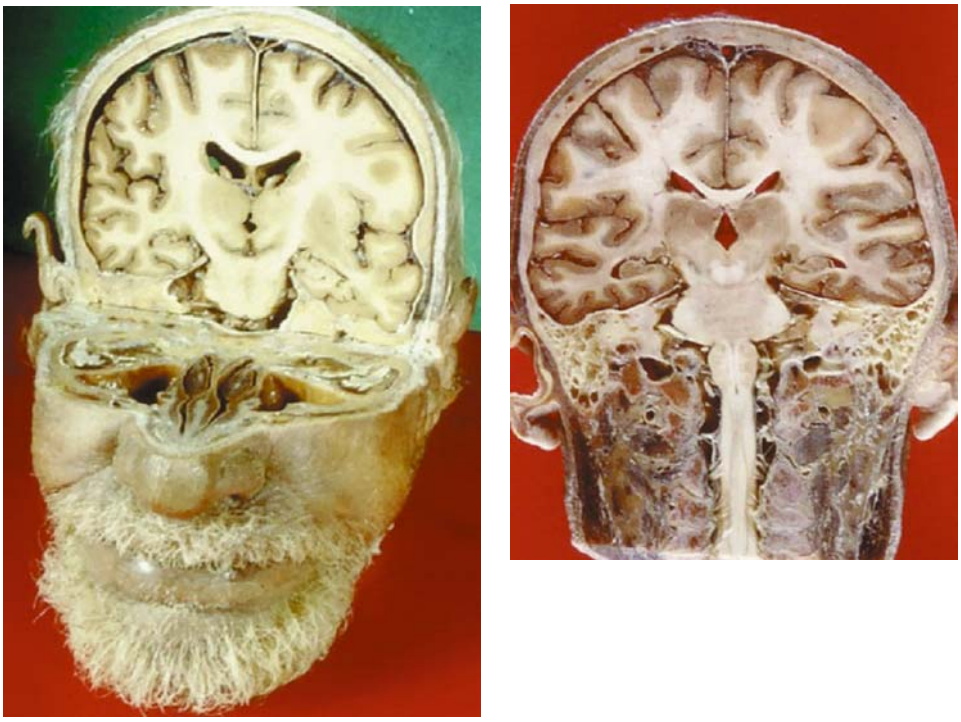


Fig. 5. What does the skull-box contain?

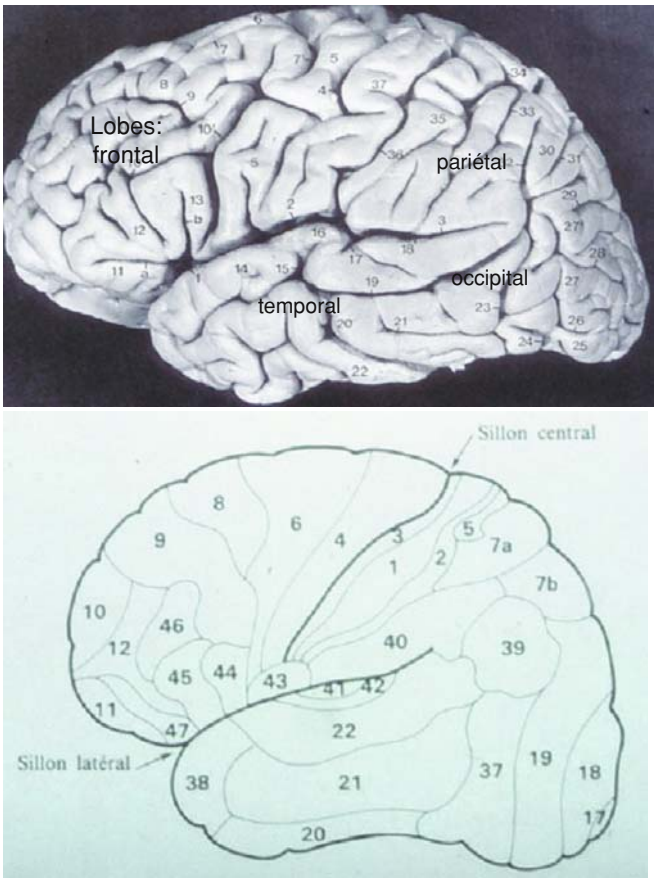


Fig. 6. Lateral aspect of the brain: the folded gyri of the cortex allow to obtain more surface for the neurons. Every area of the brain has a preprogrammed functional specialisation.

movement, gradually covering the diencephalon and generating the particular spiral shape of the caudate nucleus and lateral ventricles. In the foetus and newborn the growing suture lines are straight, but the exocranial side of the suture gradually becomes sinuous in relation to the tangential forces of the muscles of the neck, which allow to support actively the head, and also of the masticatory muscles, which become more and more powerful with age. The endocranial side remains straight despite the continuous, progressive growth of the brain. When the hemispheres stop growing, roughly at the age of twenty, the suture lines close starting with the endocranial portion. After age 50 or 60, the skull is a continuous box. In children, perturbations of cerebrospinal fluid (CSF) circulation may result in parting of the suture lines, but in adults intracranial hypertension progressively alters the white matter, producing a dilation of the ventricular cavities. The mechanical protection provided by the skull is reinforced by the CSF, which is continuously produced from blood by the choroid plexus of the ventricular cavities (figure 7). Communication between the central and the peripheral part of these spaces is provided at the level of the fourth ventricle by two apertures: medial (foramen of Magendie) and lateral (foramen of Luschka). Resorption of the CSF is also continuously achieved at the level of the venous granulations described by Pacchioni along the internal side of the sagittal suture, but also along the spinal roots thanks to a fibrous fixation of the arachnoid membrane on the pia mater, which later becomes the fibrous sheath of the spinal nerves. A contrast medium injected into the meningeal space is gradually resorbed along the nerve. This means that it is not a "cul de sac" located at the junction of the anterior and posterior roots.

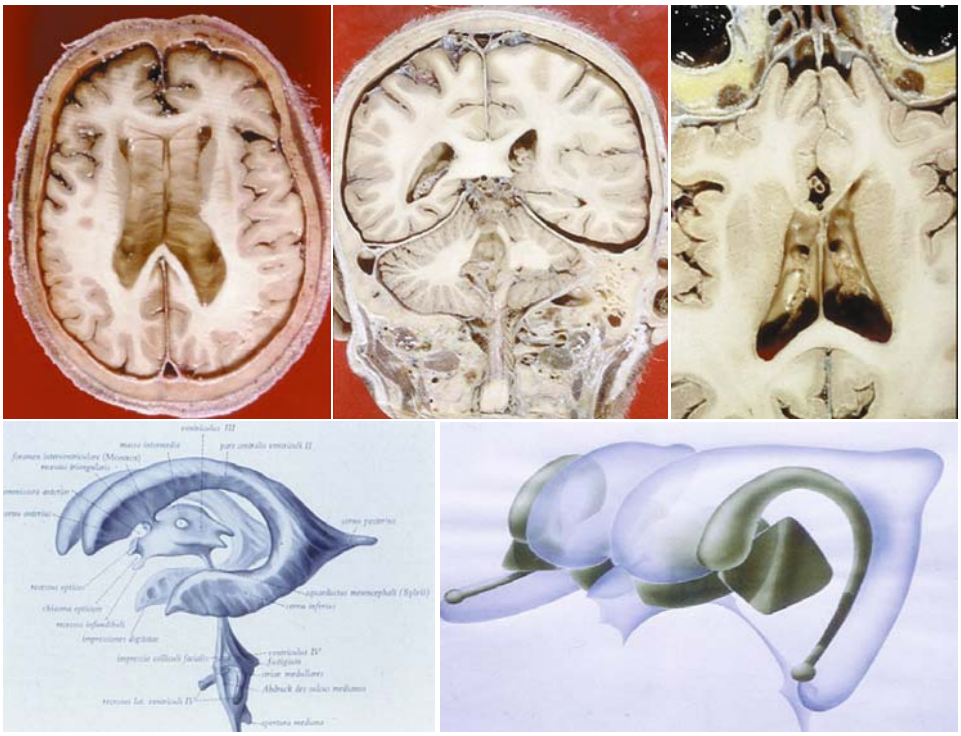


Fig. 7. The ventricular cavities of the brain.

2. THE MAIN SUBDIVISIONS OF THE ENCEPHALON

According to the international anatomical terminology and the progressive construction of the different parts of the encephalon, the following subdivision can be made:

2.1. Telencephalon: **left and right hemisphere:** main sulci: central/lateral
frontal, parietal, temporal, occipital lobes
commissures: corpus callosum
anterior commissure
interammonic commissure
(psalterium)
basal ganglia: caudate nucleus
lenticular nucleus
(or lentiform nucleus)
putamen
globus medialis
globus lateralis

2.2. Diencephalon: **thalamus**
posterior commissure
hypothalamus

2.3. Mesencephalon, metencephalon and myelencephalon:
brain stem: mesencephalon
pons
medulla oblongata
cerebellum: medial (archeocerebellum)
intermediate
(paleocerebellum)
lateral (neocerebellum)

3. THE FOUR MAIN FUNCTIONS OF THE BRAIN

For didactic reason, it is possible to distinguish four main functions that are under brain control and integrate all human activities.

3.1. Mobility

Mobility accounts for a large part of the central and peripheral nervous system, which is in charge of the command and control of segment movement and fixation. There are roughly 600 muscular actuators; some information on their technical specifications is in order if the complexity of their innervation is to be understood. The muscles are viscoelastic, which allows them to be contracted noiselessly, unlike industrial machines, but they are non-reversible, i.e. they can only be contracted in one direction up to a maximum of one third of their length, and they are non-linear. Therefore, at least two opposite muscles are required to obtain one degree of joint freedom. Although the physiologists have described a relationship between tension and length, the most important parameter in terms of brain control is the state of the muscle, identified by its stiffness in relation to only three possible states: relaxed, contracted or stretched. For a better understanding of this technical problem, in 1992 we suggested to apply some data from the field of robotics, hypothesising that the problems connected with the control of an industrial manipulator's position and movement are exactly the same as those of the control of the excursion of a hand grasping or manipulating an object in a three-dimensional space. In fact, two pieces of information are required to write the equations needed to define a robot's algorithm of command: the state of the motors, identified by the electric current or the oil pressure, according to the electrical or hydraulic nature of the actuators, and the angles of the different joints, which can be measured by potentiometers. Also in the human motor system, the brain needs to know the state of the muscular actuators and the angles of the different body segments.

Two specific transducers provide signals related to the mechanical state of the muscles. The neuromuscular spindles, which measure 1 cm in length, contain inside a fibrous capsule striated fibres around which are coiled neural endings that transfer signals to the alpha motoneurons of the anterior horn of the spinal cord through a fast monosynaptic junction. This generates the direct myotactic reflex, which is to be considered as a servomechanism of annulment of the tension of the intrafusal fibres and is particularly useful to adjust at the periphery the amount of force needed to achieve a particular task. The second transducer is the Golgi organ, a force transducer responsible for the inverse myotactic reflex, a protection reflex against muscle overtension. These two reflexes are under the control of supraspinal centres, signally the corticospinal and rubrospinal tracts, which explains the spasticity, resulting from the lack of inhibition of the fusal servomechanism, observed in the case of spinal cord resection or of destruction of motor and somatosensory cortical area, as in stroke. As regards the joint angles, the muscles cannot provide this information for two reasons: first, they are viscoelastic and redundant; secondly, the brain does not store the geometric coordinates of the muscle insertions in relation to the axis of the joints, which would allow to measure the angles. The ligaments, which are very rich in mechanoreceptors, cannot play this role due to their redundancy for a particular joint. Therefore, they are rather indicators of the extreme position of a joint. The technical solution is to use the "transducer dress" covering the body as a goniometer. Indeed, thanks to the Ruffini corpuscles, sensitive to stretch forces and exhibiting almost the same structure as the Golgi organs, the skin around all the joints can, by its deformation during movements, measure the angles and provide conscious perception of the position and movement of all body segments in a static, dynamic and cinematic

manner. A non-sensitive segment cannot be integrated in the brain control system, clearly demonstrating the strong functional link between motor and cutaneous sensitive pathways. This is particularly evident at the level of the cortex. Thus, the gyrus precentralis (area 4) contains a representation of all the muscles of the body according to a topographical code. This was identified by the Canadian neurosurgeon W. Penfield using electrostimulation during neurosurgical procedures on more than 1000 patients and called "homunculus" due to its peculiar shape. In it, the large representations of the face, in relation to language articulation, and of the hand contrast with the very small area devoted to the lower limb in the paracentral lobule within the medial aspect of the hemisphere. This can explain why, after a stroke, a hemiplegic patient can rapidly recover some locomotion but not the use of the hand, the lower limb functioning on a semi-automatic mode to a greater extent than the hand. Just behind the precentral gyrus, which represents the "motor keyboard", is the postcentral gyrus (areas 1, 2, 3, 5) of the parietal lobe. This is the "sensitive keyboard", where all the skin zones of the body are represented according to the same topographical code. In fact, a functional loop, which can be called statokinetic loop, links these two gyri, providing data on the position of all body segments. A tumour in the parietal lobe can give rise to asomatognosia, where the patient is not paralysed and can move the limbs but cannot perceive their exact position without visual control.

As mentioned above, even without knowing anything of the body's motor hardware and software, the driver of the human machine can achieve very complex tasks that justify the two levels of motor control. The first is the decisional area, which works consciously and employs a global language exclusively in terms of movements and never in terms of muscles. For example, gaze control with foveal fixation – located within the premotor area – integrates all the coordination processes that allow to move the body around the point in space chosen by the subject. The second level is the execution area, operating in an unconscious mode and accounting for roughly 80% of the motor circuits; this employs an analytical language corresponding to all the automatisms, servomechanisms and closed-loop regulation circuits needed to perform motor tasks. Three technical problems need to be solved at this level: the appropriate choice of the muscular actuators, agonist/antagonist adjustment,

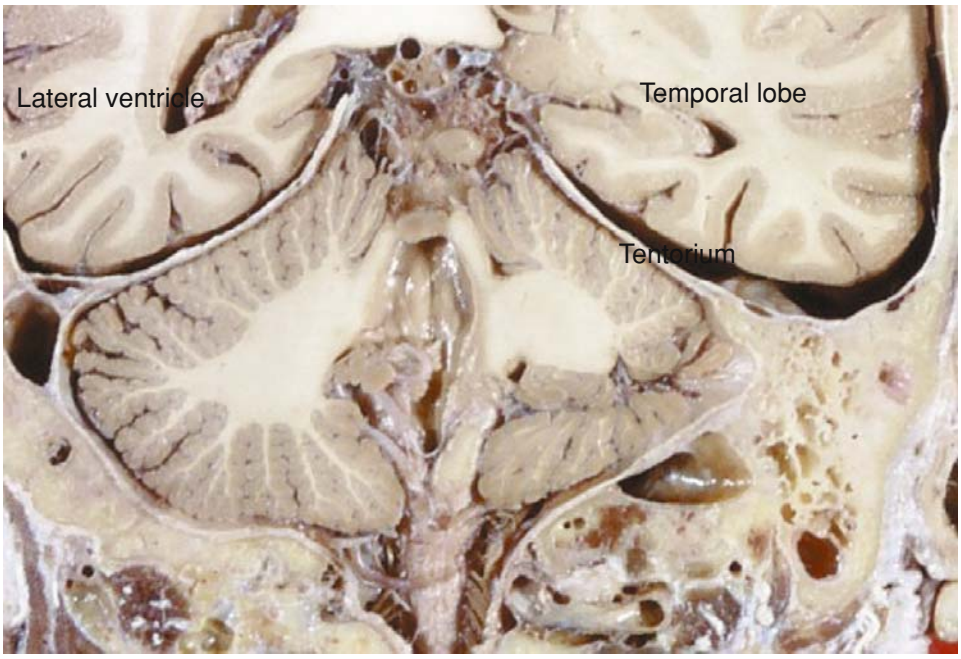


Fig. 8. The cerebellum: central unit for the mobility management

and error correction in real time. The driver is unaware of the right muscles for a given task; thus, starting from the decisional area of action, a special circuit goes from the premotor area to the motor thalamus, then to the lateral cerebellum, where the motor programme is organised (figure 8), and back to the motor cortex to type the group of required muscles on the motor keyboard, finally reaching, through the corticospinal tract, the correct level of metameric motor activation. A complementary circuit connects the cortical area to the basal ganglia (caudate nucleus and lenticular nucleus), which store all the motor programmes created by training and education, like bicycling, playing the piano, etc. Agonist/antagonist adjustment is performed in the intermediate cerebellum in conjunction with the red nucleus and the substantia nigra, responsible for dopamine secretion. The spinocerebellar sensitive pathways provide the goniometric information, explaining the hypermetria and adiadocokinesia seen in intermediate lesions of the cerebellum. Error correction in real time is performed by the inferior olive, a large, sinuous band of neurons of the medulla oblongata, which receives signals from the level of the spinal cord that has been activated and transfers orders to the Purkinje cells, which have up to 200,000 neural connections.

Finally, in this multilevel heterarchical mobility control system, the close interaction between sensory inputs and motor outputs makes it impossible to study them separately. In addition, one of the main keywords is automation, which allows to perform without an excessive workload for the driver complicated functions like the vertical posture. By definition, a biped is unstable and continuous position corrections are needed to guarantee the balance. This is done automatically by the postural servomechanisms, which receive information from three sensory levels (eyes, skin and vestibule) and activate the appropriate muscular counter-reactions by impulsions to stabilise the body in monopedal or bipedal posture.

3.2. Communication

This function occupies a large part of the brain and consists of three main aspects: sensory inputs, expression outputs and in between the cerebral black box related to the ignorance of the human driver.

A. The sensory inputs

They come from the sensory organs, which transfer to the brain the specific information of vision, hearing, touch and olfacto-gustation.

The visual system belongs to the diencephalon, and the retina is a modified cortex endowed with the same number of layers. The optic nerve is not a cranial nerve, but a central pathway surrounded by the meningeal sheaths as far as the eyeball. We have two eyes and see a single image, which represents the technical problem of stereoscopy whereby we perceive the third dimension of space. This implies a perfect fusion of the two retinal images, which is achieved by two systems. First, the optic chiasma, where 50% of optic fibres cross in man and primates, mixing the temporal sector of one eye with the nasal sector of the opposite eye. Therefore, each hemisphere sees a visual hemifield. In addition, along the visual axis the retina has a high-resolution point called macula or fovea, a little crater with a high concentration of cones (135,000 / sq mm) accounting for 80% of vision. Surrounded by a low-resolution retina, this point allows to fuse very precisely the two images. All the animals endowed with a punctiform macula have stereoscopic vision; the most exciting case is that of the chameleon, which has both types of vision: panoramic with two different images and stereoscopic with a very useful three-

dimensional perception for catching a prey by projecting forward the tongue. Beyond 30° of movement of the eyes, stereoscopy becomes impossible due to parallax problems and to the presence of the nose. The technical solution is to move the head together with the eyes, which is performed by the eye-head servomechanisms. But in order for the brain to coordinate the two movements, head position and displacement have to be identified. This is probably the reason why the vestibule, which is a three-dimensional angular and linear accelerometer, is located in the skull base and fixed very early, the ear being in fact the first organ to complete its growth at birth.

Before going through the optic radiations to the primary visual cortex of area 17, located along the calcarine fissure in the occipital lobe, the two retinal images are integrated for shape and colour in the lateral geniculate nucleus on the lateral side of the thalamus. This has six layers, three for the temporal and three for the nasal sector. The superior colliculus is connected with the retina and manages the functional link between visual input and mobilisation of the eyeballs using the III, IV and VI cranial nerves on both sides. Area 19 is where the selected images are stored.

The ear has two completely different functions (figure 9): hearing and the static and dynamic stabilisation of the head with two nerves, cochlear and vestibular (VIII). The hearing ear is characterised by the transition between air, occupying the external auditory meatus and middle ear, and fluid, endolymphatic in the cochlear canal, which contains 13,000 external and 3000 internal ciliary cells, and perilymphatic in the tympanic and vestibular ramps. The vibrations in the air are picked up by the tympanic membrane, amplified by the ossicular chain (malleus, incus and stapes), and transferred to the cochlea, which is a frequency analyser (20 to 20,000 Hertz). Then the coded signals go through five neuronal relays (spiral ganglion, ventral and dorsal cochlear nuclei, medial and lateral superior olivary nuclei, trapezoid body, inferior colliculus, medial geniculate nucleus) to become sounds perceived at the level of the first temporal gyrus (gyrus of Heschl), the primary projection of hearing. Of the many details of the structure of the auditory system, two are

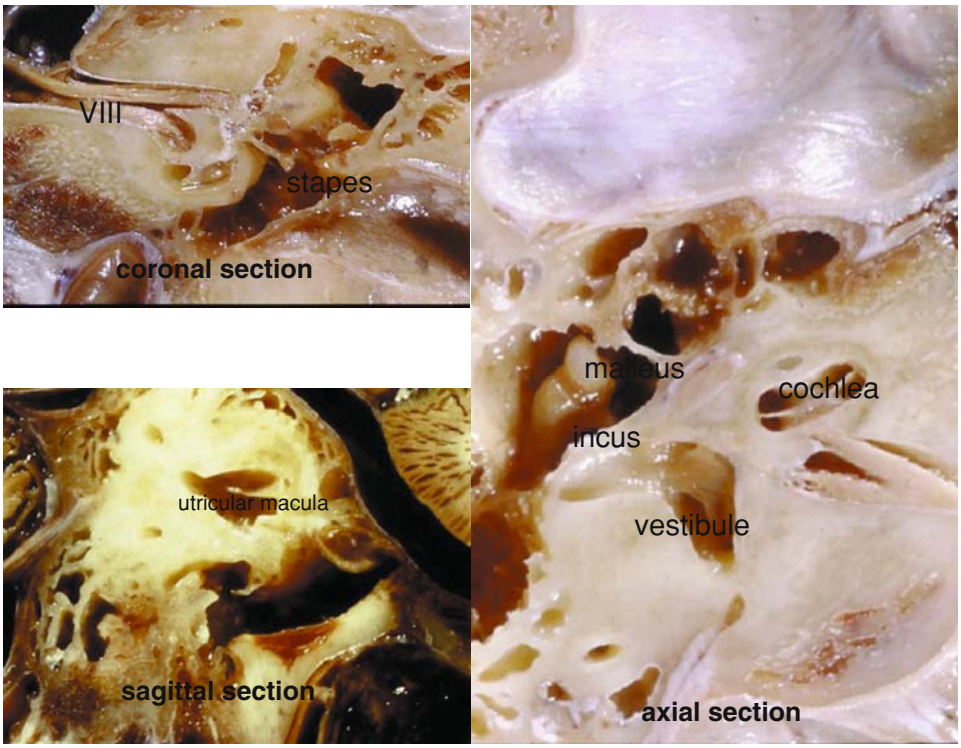


Fig. 9. An exemple of sensory input: hearing

particularly intelligent, conclusively ruling out random organisation. To optimise reception of vibrations by the tympanic membrane, this clever system maintains an equal pressure on both sides of the membrane. The auditory tube (Eustachian tube) – connecting the middle ear to the nasal pharynx – is kept open by two muscles when the larynx is not functioning so as to avoid perturbation of tympanic activity due to the transfer of vibrations on both sides of the membrane. The soft palate closes the nasopharynx during vowel emission without opening the auditory tube through contraction of the sole levator veli and, mainly during swallowing, the tube is kept open by the joint contraction of both levator and tensor veli. The levator veli is logically innervated by the glossopharyngeal nerve (IX) and the tensor by the trigeminal nerve (V) as a masticatory muscle. The second technical detail relates to the cochlea. The transfer of the air vibrations into the vestibular ramp by the stapes requires solving the problem of the end of the tube. If this is rigid, the vibrations return to their origin, giving rise to an echo effect that deeply disturbs the frequency analysis made in the cochlear canal. The optimal technical solution is to absorb completely the vibrations; this is achieved first by the diameter of the ramps, which decreases in the vestibular ramp until the top of the cochlea (helicotrema) and then increases in the tympanic ramp up to the end, where lies the round window closed by the secondary tympanic membrane, which completely absorbs the vibration train. This small technical detail, which is critical for the correct functioning of the ear, cannot be explained without an intelligent pre-programmed blueprint.

The tactile inputs are very rich, in line with the large number and variety of skin transducers going from the free endings of the epidermis to the diverse corpuscles of Wagner-Meissner, Vater-Pacini, Krause and Golgi-Mazzoni. The diameter of the myelinic fibres, up to a maximum of 25 µ, determines the velocity of the transmission of touch, pain and temperature information associated in the spinal pathways. The ascending tracts go to the thalamus, cerebellum and reticular formation. Thalamic filtration provides for the selective orientation of signals to the different cortical areas, with pain signals having priority. Tactile detection of objects, combining sensation and movement, corresponds to haptic perception.

Olfaction is combined with gustation and pertains to the telencephalon. There is in fact no cranial nerve. The olfactory bulb is connected to the 40 million neurons of the olfactory portion of the nasal mucosa. Smell discrimination is performed at the molecular level and transferred to the mitral cells and then to the olfactory cortex: the lateral olfactory area (areas 34 and 38) corresponds to the dorsomedial part of the amygdala at the level of the uncus and to the medial olfactory area in the septal area (area 25), which is integrated in the limbic system, explaining the close relationship between smell and emotions. The associated taste informations related to the tongue receptors is relayed from the gustatory nucleus in the brain stem to the temporal lobe.

B. The cerebral black box

The human driver can choose the subject of his thought without knowing how the connections are made in the different cortical and subcortical areas. Therefore, the brain is a very rich association network endowed with different association pathways described by the anatomists, which are visible on brain images: arcuate between frontal and temporal cortex, superior occipitofrontal between occipital, parietal and superior frontal cortex, uncinate between the temporal lobe and the anterior part of the frontal lobe. The callosal commissure, with its 200 million fibres, links the two hemispheres.

This complex associated multimedia network manages all aspects of psychic life, among which consciousness, which is not located in a particular zone of the cortex but requires a critical number of cortical columns after the switch

on operated at the level of the brain stem. The three items "who, when, where" are typical of the basic consciousness that many animals also have. But there are different degrees to it, and only man has the capacity to speculate and to proceed to concept and abstraction. Mathematics is probably one of the most specific human creations. Intelligence, which can be defined as the ability to understand and resolve a problem, is obviously related to the brain organisation and, as demonstrated by the various imaging techniques, to the volume and the surface of the cortex, which are variable among individuals. Morphological brain studies are becoming more and more precise, and our understanding of quantitative data can be improved by relating them to individual psychic profiles. It is interesting to note that brain activity cannot stop without resulting in death, which justifies the dream activity detectable by EEG in relation to the depth and type of sleep.

Although Gall introduced a theory of brain localisation, the modern tendency is to hold that many cortical areas are highly specialised, for instance for the recognition of words, numbers or faces. This has explicitly been demonstrated by the analysis of pathological cases through clinical observation as well as modern imaging techniques.

C. The expression outputs

Owing to the action part of communication and exhibit three modalities: written and oral language, mimicry and behaviours.

Language, as shown by Paul Broca in 1861 and later by Carl Wernicke, consists of two main functional subdivisions: the articulation of phonemes and sentences in the inferior frontal gyrus, with its three parts, opercular (area 44), triangular (area 45) and orbital (area 47), and the semantic function for the recognition and understanding of oral language, located in the angular, supramarginal and perisylvian temporal gyri and in the insula. Speaking requires the control, from mouth to larynx, of 35 different muscles. It seems logical to have a dominant side in the motor language centre to synchronise the symmetric musculature. This centre normally lies in the hemisphere of the dominant hand, which can write the different memorised letters and words and requires a particular education programme. Talking without speaking is also possible by distinguishing between endolanguage, which is really the instrument of the mind (no mind without language), and exolanguage, which is the social expression of the mind. Accordingly, two clinical types of aphasia have been described based on distinct localisations of brain lesions.

Mimicry is produced on the face by deformation of the skin around the eyes and mouth, thus highlighting the importance of the facial nerve (VII), commanding the skin muscles, and of the trigeminal nerve (V), responsible for sensitive feedback for mimic control, which is associated with a gesticulation that is particularly expressive in the Italian people. Specific behavioural reactions (agreeing, attacking, escaping) stored in the limbic system are also associated with communication.

3.3. Biological maintenance

Owning to the lack of awareness by the human driver, all biological maintenance services are automated: breathing cycle, cardiac rhythm and blood pressure regulation, intestine mobility, metabolism (anabolism and catabolism), kidney depuration, endocrine regulations. This is achieved by a special nervous system, the vegetative or autonomic system, which has a management centre in the hypothalamus and two complementary but opposite vectors, the sympathetic and parasympathetic systems. Among the maintenance services, some work 24 hours a day, like the two breathing centres located within the brain stem. This justifies the particular protection of the

arteries supplying it, the vertebral arteries, which run in the cervical spine from C6 and then cross the craniocervical cardan. This joint provides for the precise movement of the eye-head servomechanism in the two main directions of visual exploration: vertical and horizontal. But the extension / rotation of the head creates a compression and stretching of one vertebral artery that result in a critical reduction of blood flow. The technical solution guaranteeing a continuous blood supply to the brain stem is the unique convergent anastomosis of two important arteries onto a single trunk, the basilar trunk. Voluntary apnoea cannot be maintained for long because the reduction in PO2 and the increase in PCO2 trigger an alarm making the respiratory muscles and particularly the diaphragm start to work again. In addition, the brain stem manages all the coordination mechanisms for vision, hearing, swallowing, micturing and sleeping. Although not all brain stem nuclei and pathways are visible on MRI, their minor variability allows to predict the location of these structures with a high degree of precision using anatomical atlases like the one by Henri Duvernoy.

3.4. The survival kit

Survival has two aspects and one logical strategic consequence. Its basic principle is an important, novel parameter: pleasure as the motor of survival. The creation of a biological need induces a pleasant feeling when it is being satisfied. The search for food is critical to survive as individuals. The search for a partner to copulate with is the condition to maintain the species over time, even though the single individuals do not understand the real motivation and the precise mechanism of the procedure, as is the case of all animals and of some humans. The strategic consequence is the need to identify, mark and defend a territory. The whole survival kit is integrated in the limbic system. It includes what Papez described as the emotions circuit: hippocampus / fornix / mamillary bodies / mamillothalamic tract / anterior thalamus / cingulate gyrus. In addition, especially in animals, the rhinencephalon is responsible not only for the search for food but also for the identification, based on pheromone secretion by the female during the fertile oestrus, of the right time to

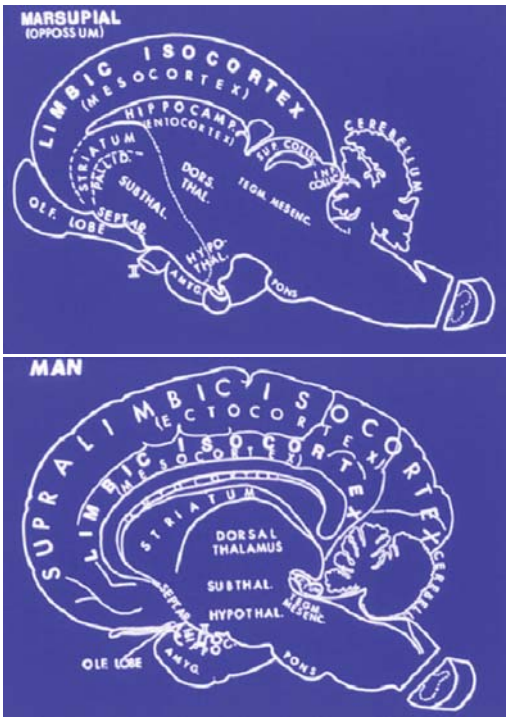


Fig. 10. Some animals have only a limbic cortex, which makes them spend all their time eating, copulating and defending a territory where they can find food and partners. Man also has a supralimbic cortex which enables control and allows him to refrain from following blindly the pressing demands from the survival kit. But… not always successfully!

copulate. In animals olfaction is really the essential survival sense. This automated process is not preserved in the human species, where there is no theoretical or biological limitation to sexual intercourse. In addition, the human olfactory system is considered as regressive compared with the macrosmatic animals, but its perception ability is more corticalised and plays an important part in cultural acquisitions, like gastronomy and perfumes. Thus, some animals only have a limbic cortex prompting them to eat, copulate and defend their territory. Man has a supralimbic cortex (figure 10), which is more or less able to check the natural survival limbic drives. This supervisory control does not always work and the territoriality expressed by the need to mark with sophisticated fences houses, cities or countries and to wage wars with terrifying means of destruction is a pre-programmed feature at all levels of human communication. Jealousy, which is the poison of love and an acute expression of territoriality, also exists in all relationships, in the home, at work, in politics, in sports and, of course, within the University.

In conclusion, the state-of-the-art knowledge of the internal brain organisation currently allows to hold that all the aspects of psychic life and all the processes included in what we call mind as well as all biological functions are closely related to brain architecture. No brain means no mind, and death – the end of the game for us all – is really the end of biological life. Anyway, the necessary correlation between anatomy and neuroimaging is the best justification of this atlas, where the radiologist can find the localisation of the most important brain structures with their possible pathological changes. The aim of the introductory chapter is to try to explain the logic of the brain's construction and how the functions that we observe can be understood in terms of centres and pathways. The close link between modern brain images, which are increasingly precise and functional (diffusion, perfusion, tractography...), and clinical investigations requires a common language for mutual exchanges. We hope to have efficiently contributed to this goal.

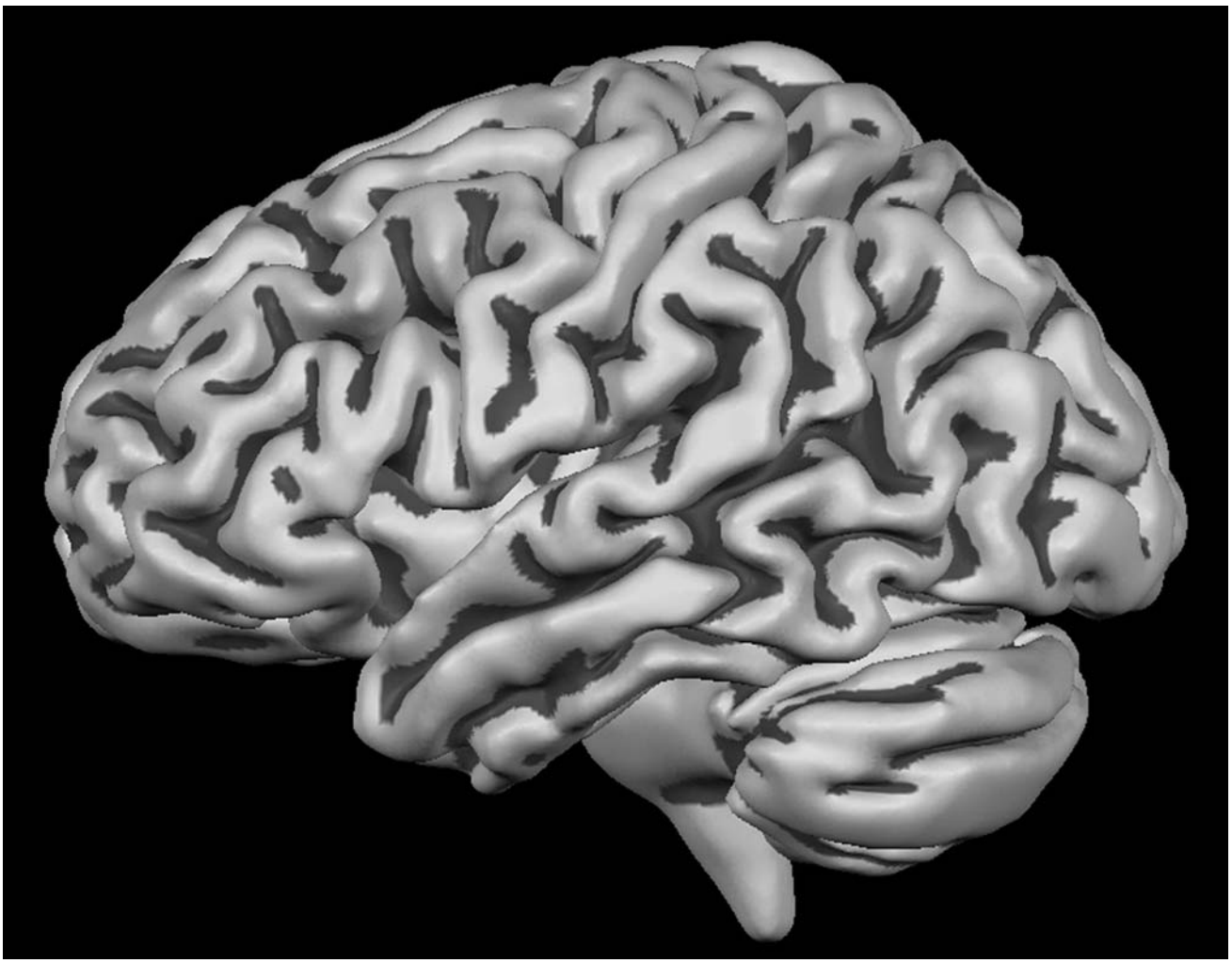
Pierre Rabischong

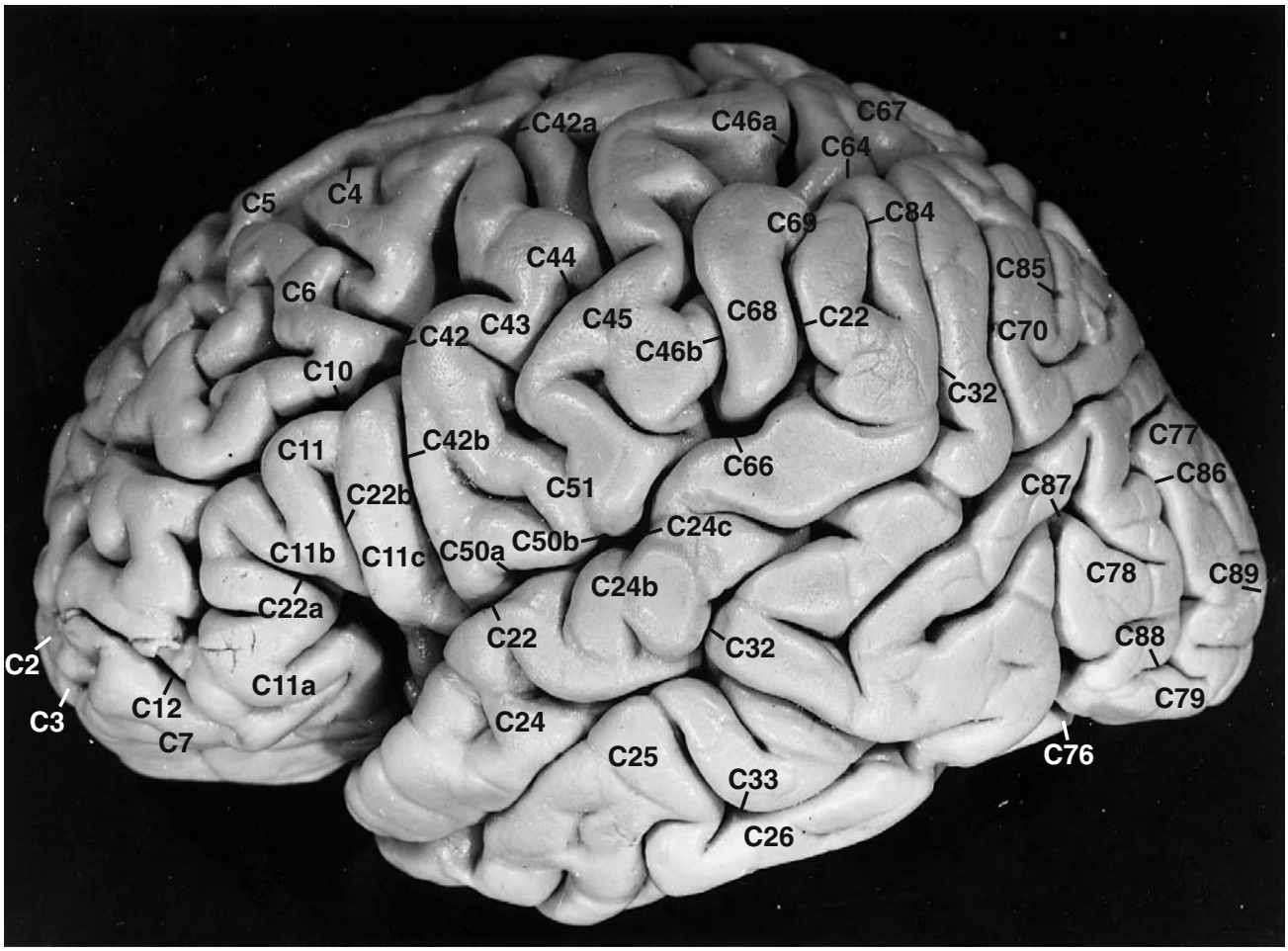
MORPHOLOGY ATLAS

SURFACE IMAGES

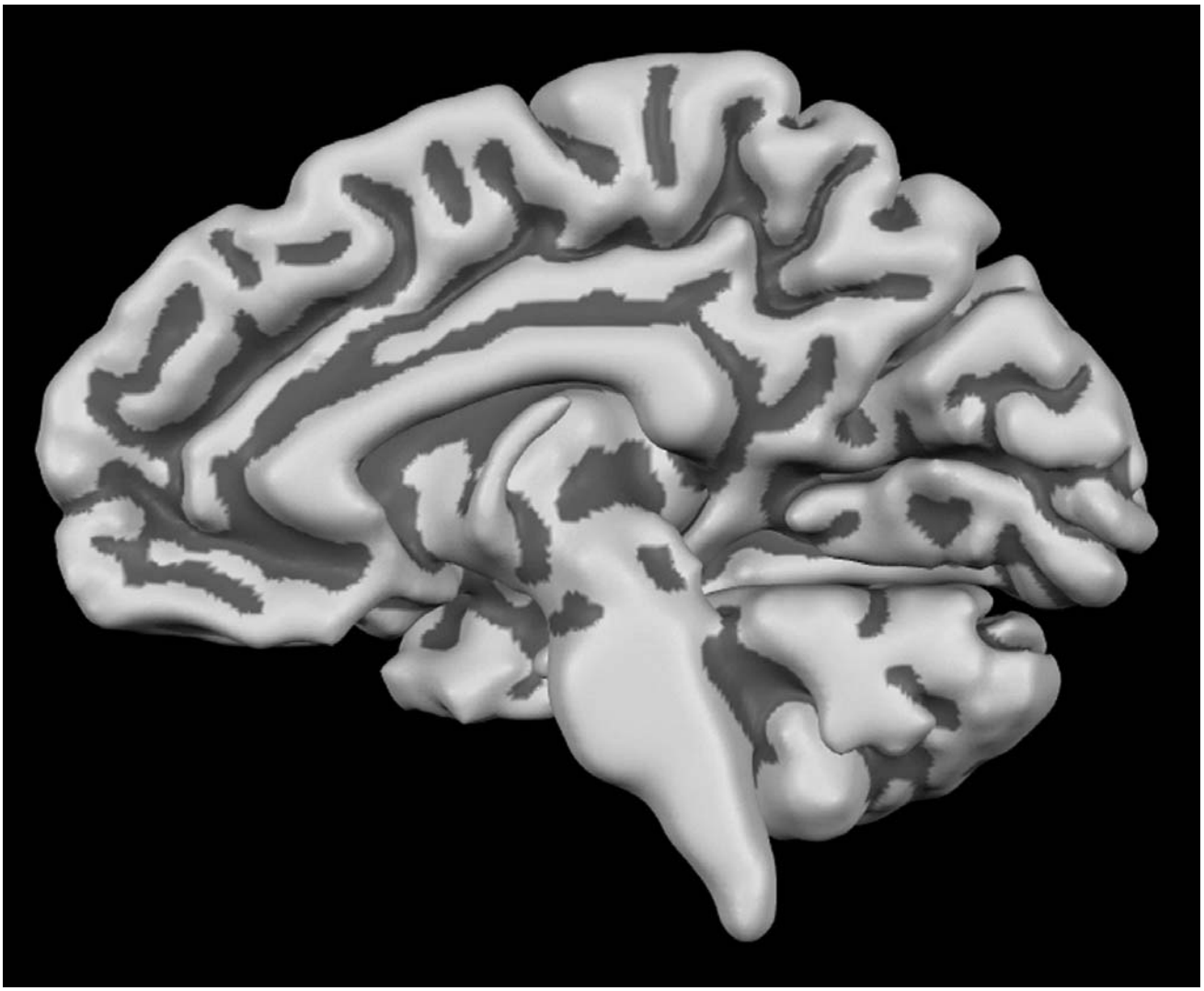
In the following pages (24–33), 3D MR surface rendering (left) is compared with "traditional" anatomical dissection. 3D T1-W MR data are processed with the Brain Voyager software.
See the jacket flap for anatomical references.

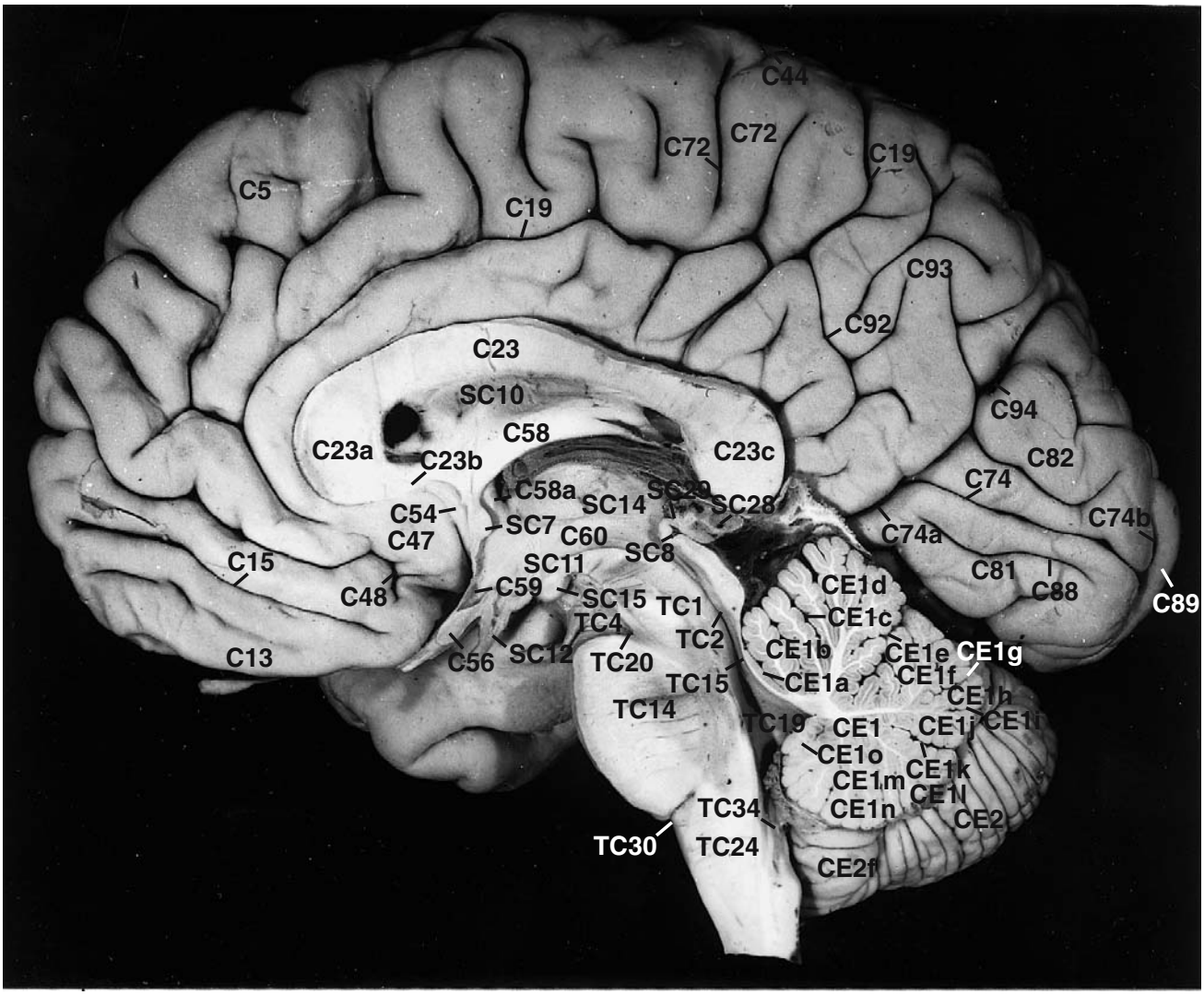
Lateral view



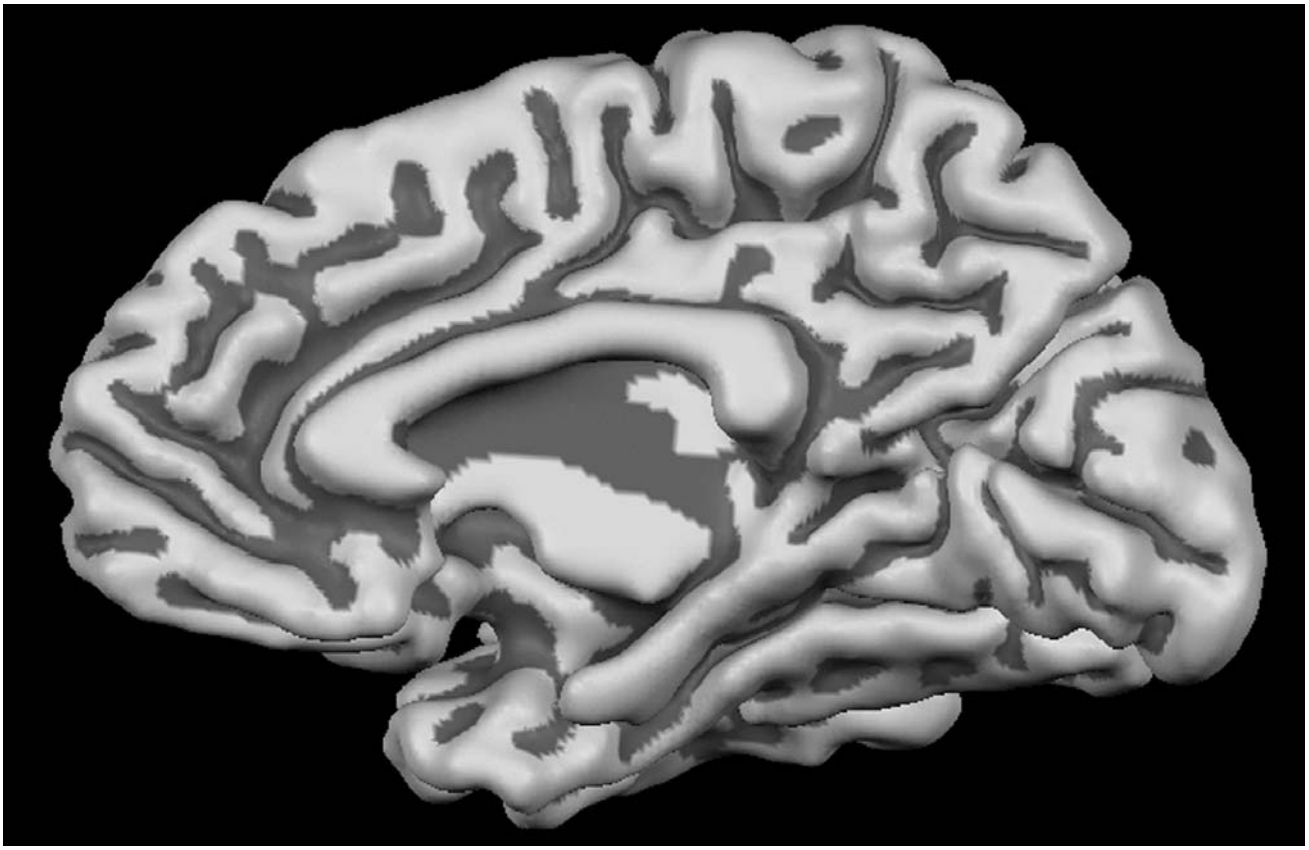

C42a
C46a
C67
C64
C5
C4
C69
C84
C44
C85
C6
C68
C22
C45
C43
C42
C70
C46b
C10
C32
C77
C11
C42b
C66
C86
C51
C87
C22b
C24c
C50b
C11b
C11c
C50a
C78
C89
C24b
C22a
C22
C32
C88
C2
C11a
C12
C79
C3
C24
C7
C25
C76
C33
C26

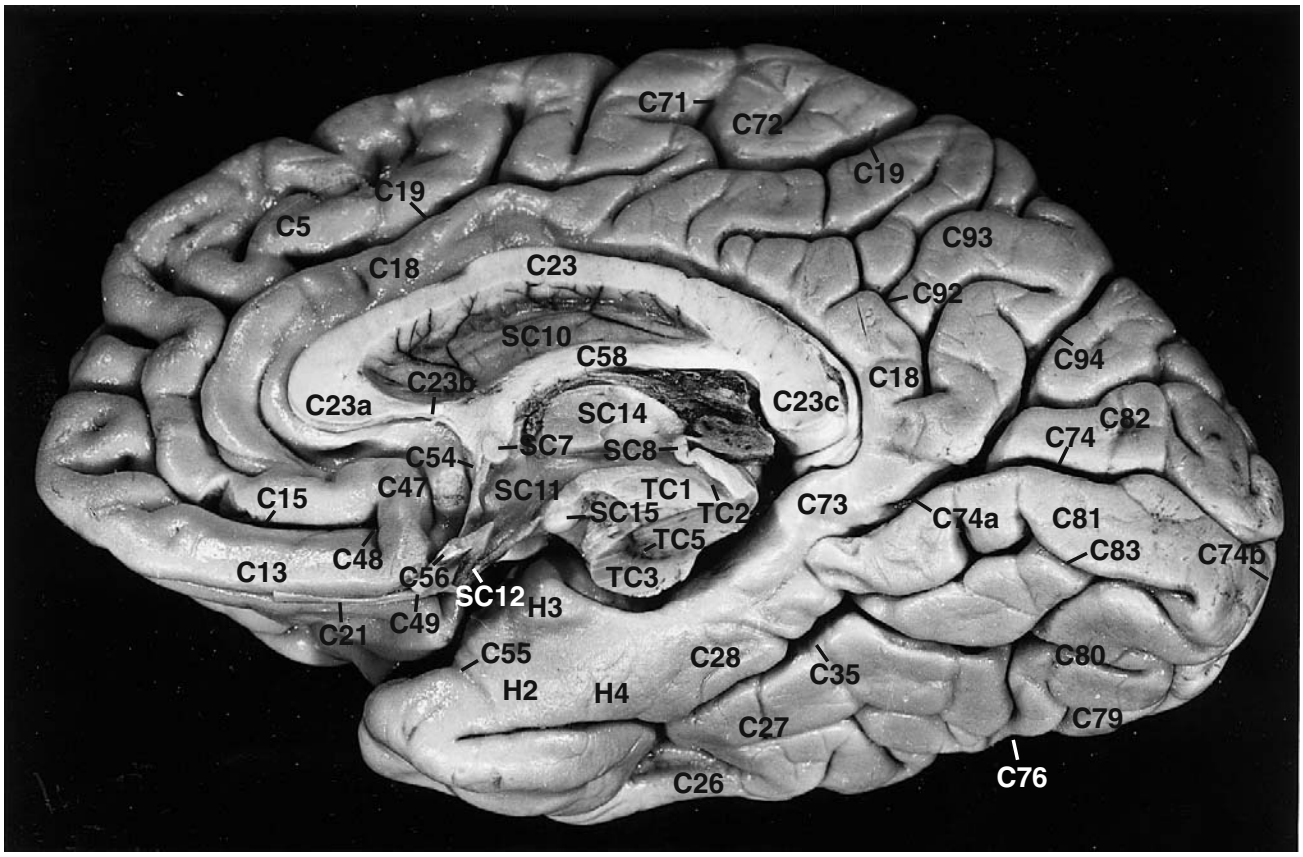
Mesial view



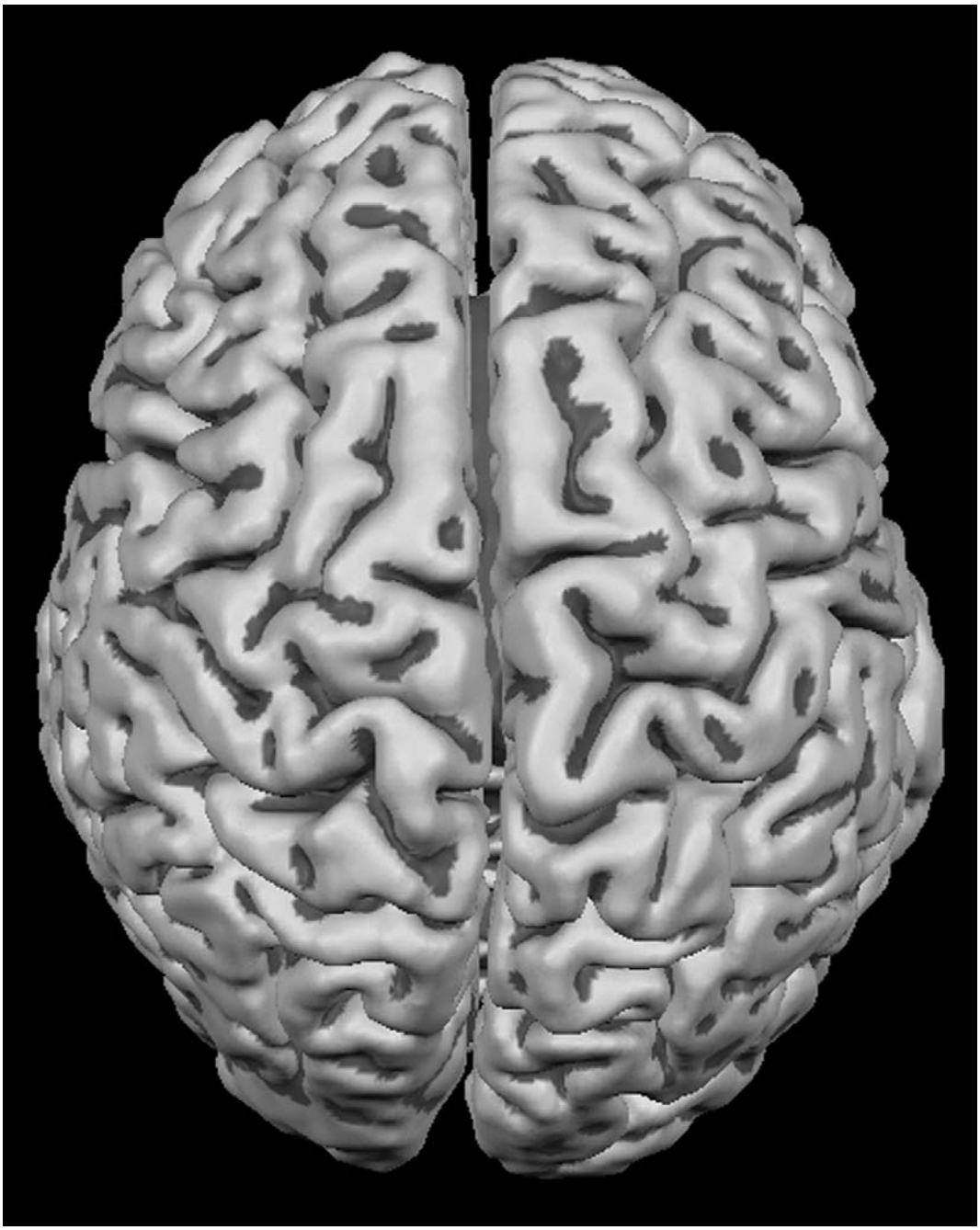

C44
C72
C72
C19
C5
C19
C93
C92
C23
SC10
C58
C23a
C23b
C23c
C94
C82
C74
C58a
SC14
SC28
C54
SC7
C60
C47
SC8
C74a
C74b
C15
SC11
C81
C88
C89
C48
C59
SC15
TC1
CE1d
CE1c
TC4
TC2
CE1b
CE1e
CE1g
C13
C56
SC12
TC20
CE1f
TC15
CE1a
CE1h
TC14
TC19
CE1
CE1j
CE1i
CE1o
CE1k
CE1m
CE1l
TC34
CE1n
CE2
TC30
TC24
CE2f

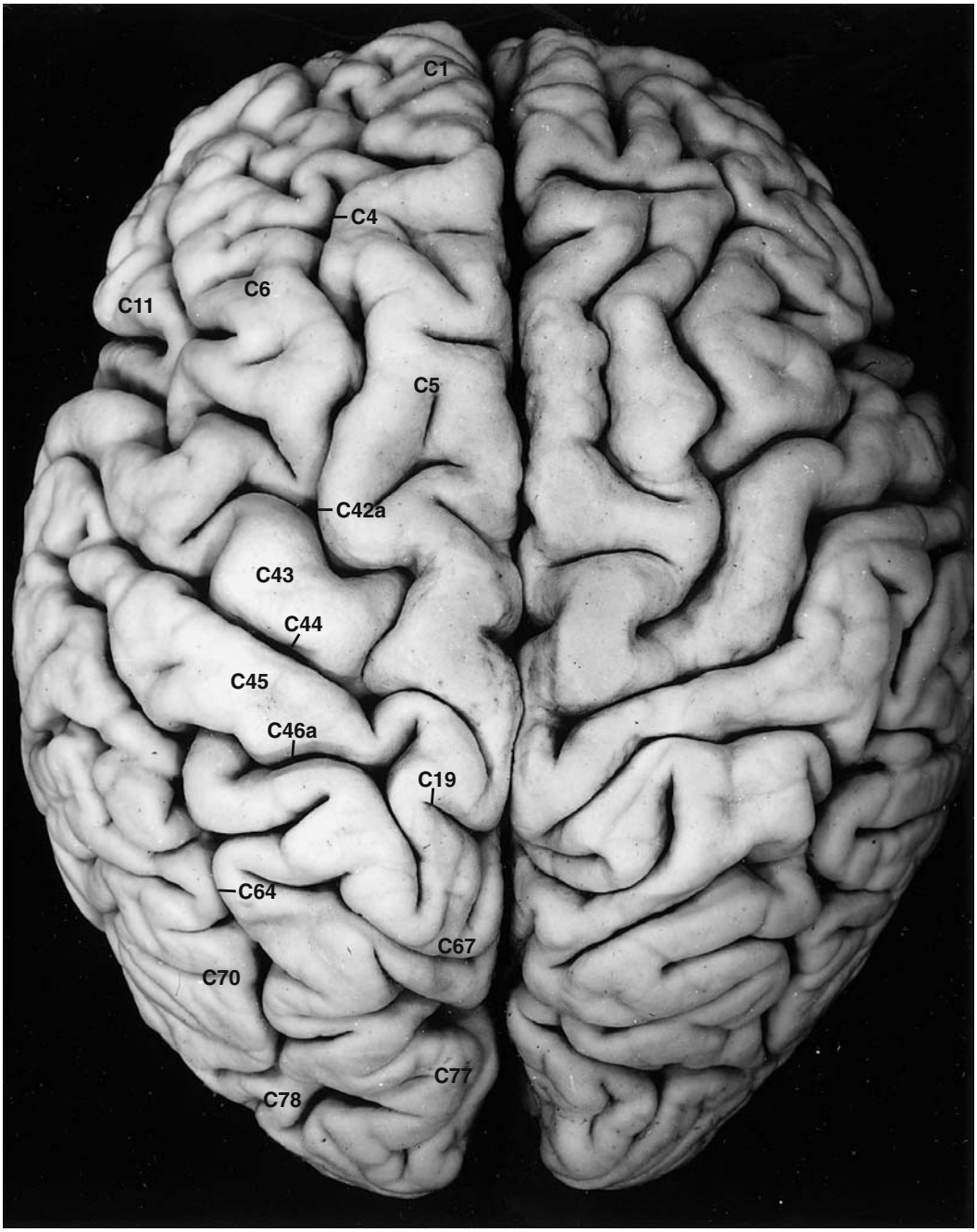
Mesial view



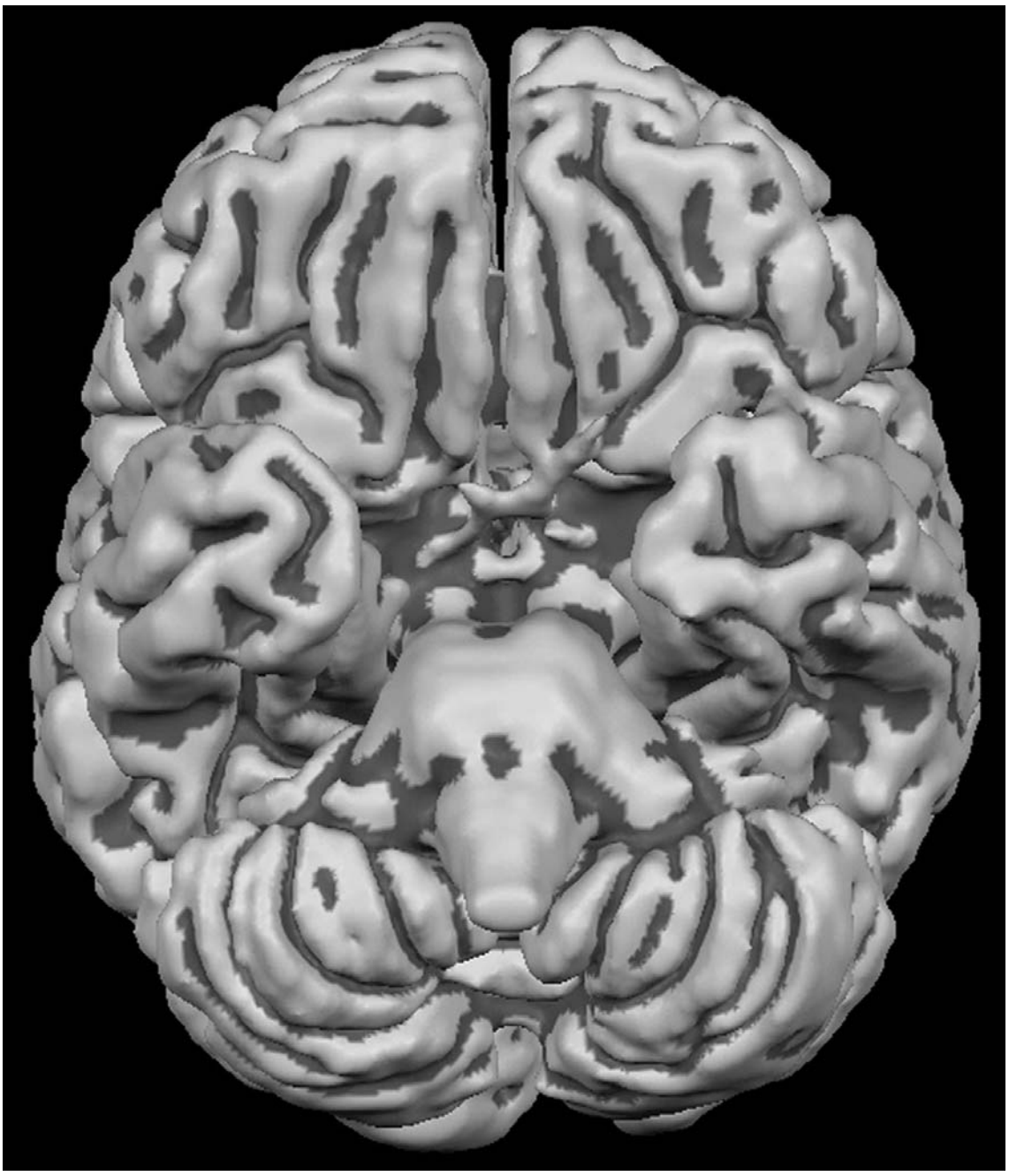

C71
C72
C19
C19
C5
C93
C18
C23
C92
SC10
C58
C94
C18
C23b
C23a
C23c
SC14
C82
C74
SC7
SC8
C54
C47
SC11
TC1
C15
SC15
TC2
C73
C74a
C81
TC5
C83
C74b
C13
C48
C56
TC3
SC12
H3
C49
C21
C55
C28
C35
C80
H2
H4
C27
C79
C76
C26

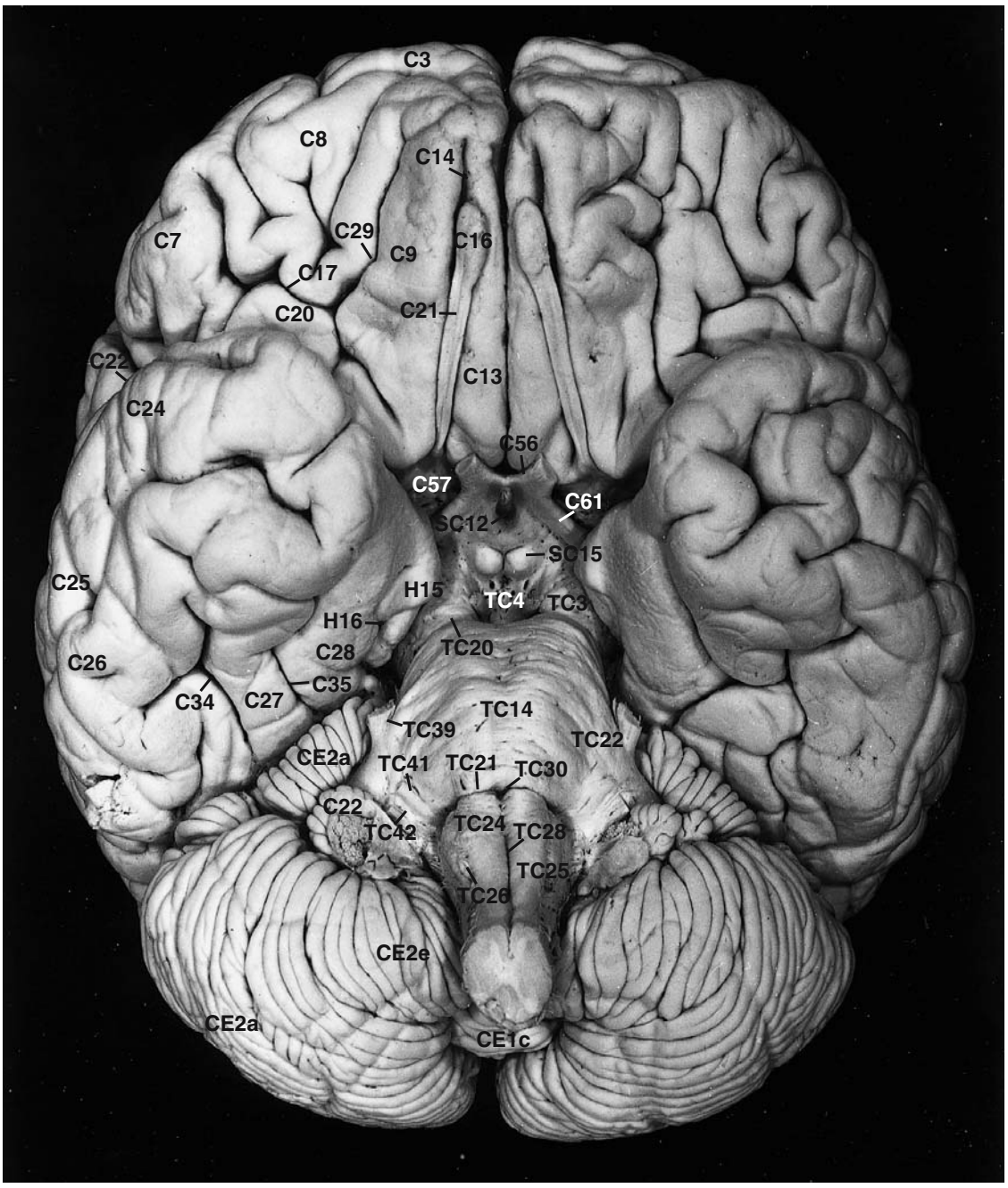
Superior view




C1
C4
C6
C11
C5
C42a
C43
C44
C45
C46a
C19
C64
C67
C70
C77
C78

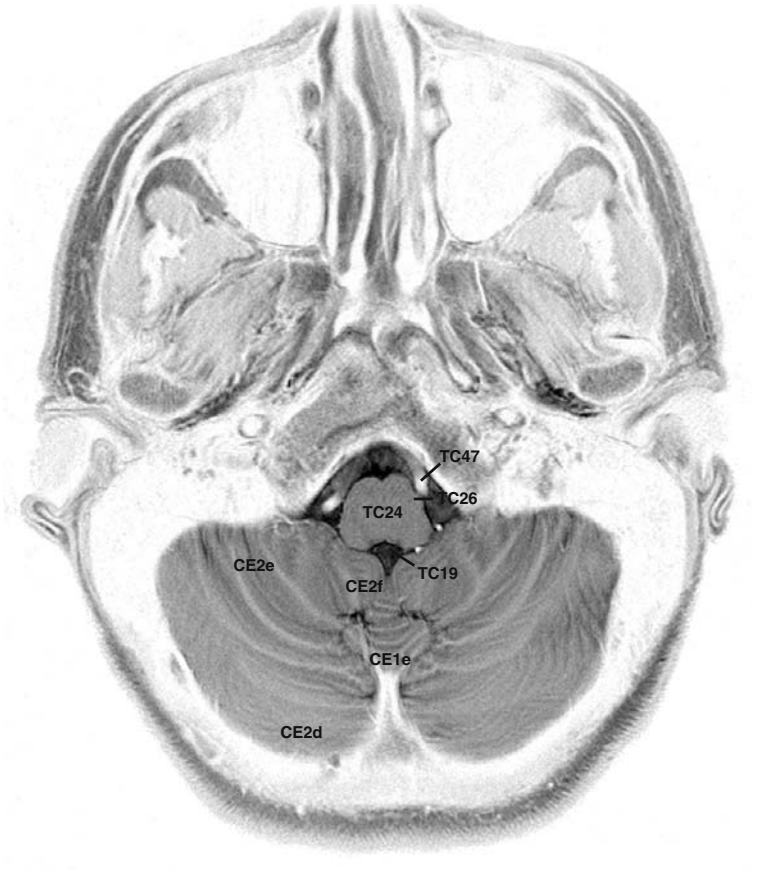
Inferior view

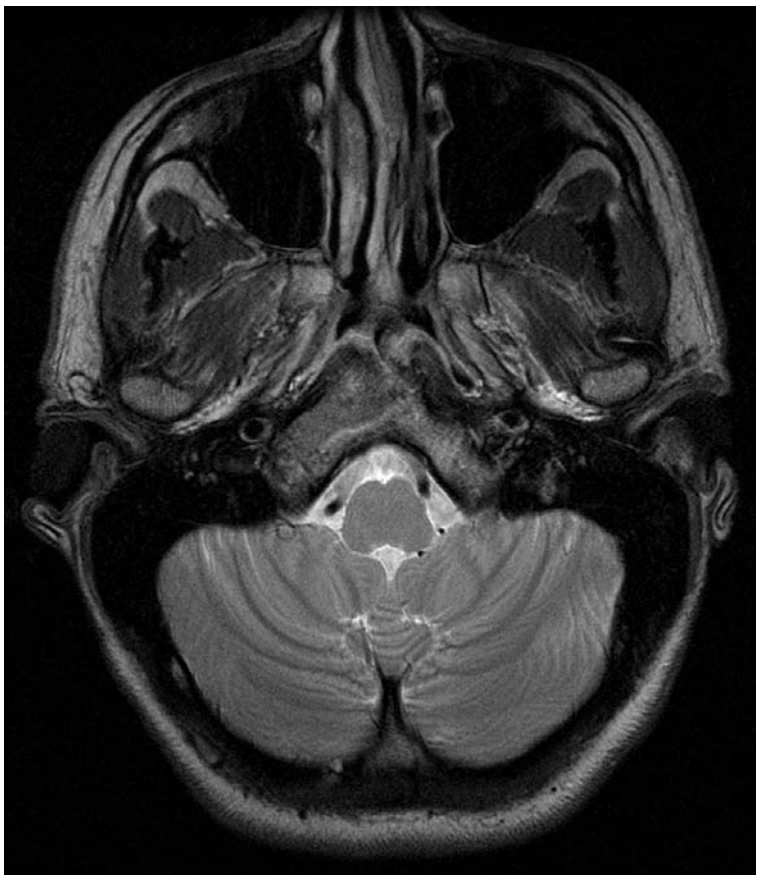


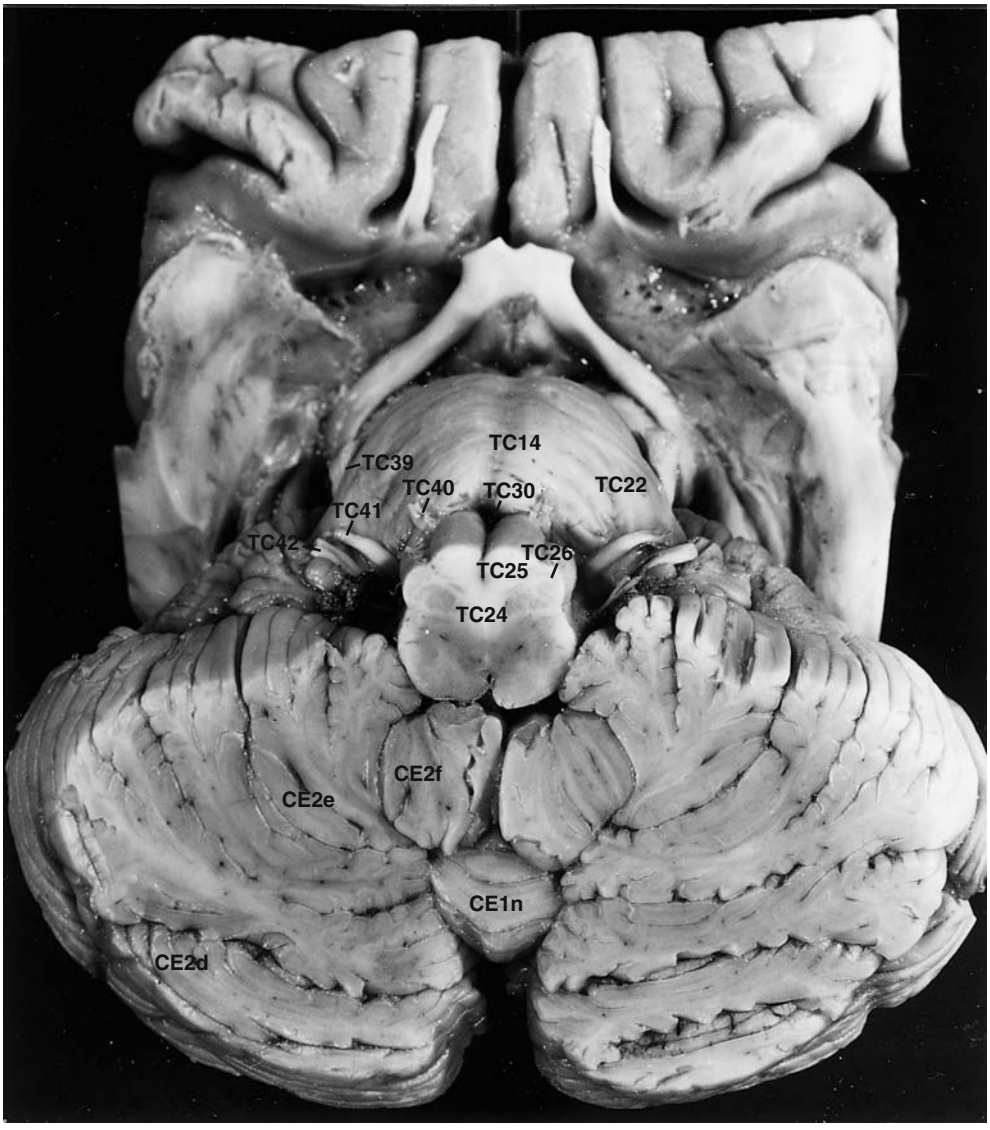

C3
C8
C14
C7
C29
C9
C16
C17
C20
C21
C22
C13
C24
C56
C57
C61
SC12
SC15
C25
H15
TC4
TC3
H16
TC20
C28
C26
C35
C34
C27
TC14
TC39
TC22
CE2a
TC41
TC21
TC30
C22
TC42
TC24
TC28
TC25
TC26
CE2e
CE2a
CE1c

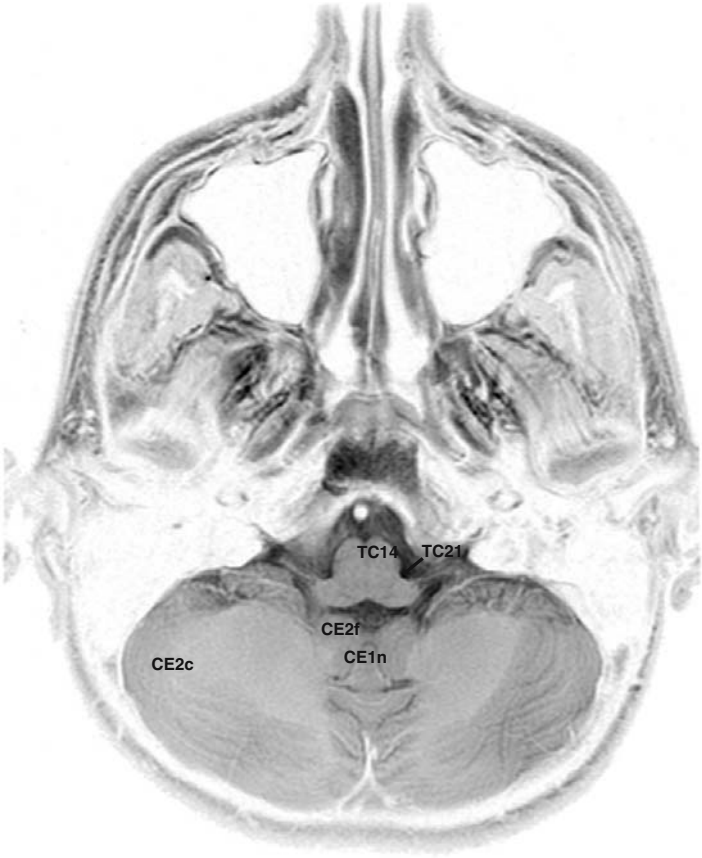
AXIAL CUTS

In the following pages (36–59), high definition T2-W FSE axial MR cuts (left) are compared with “traditional” anatomical cuts (right).
See the jacket flap for anatomical references.

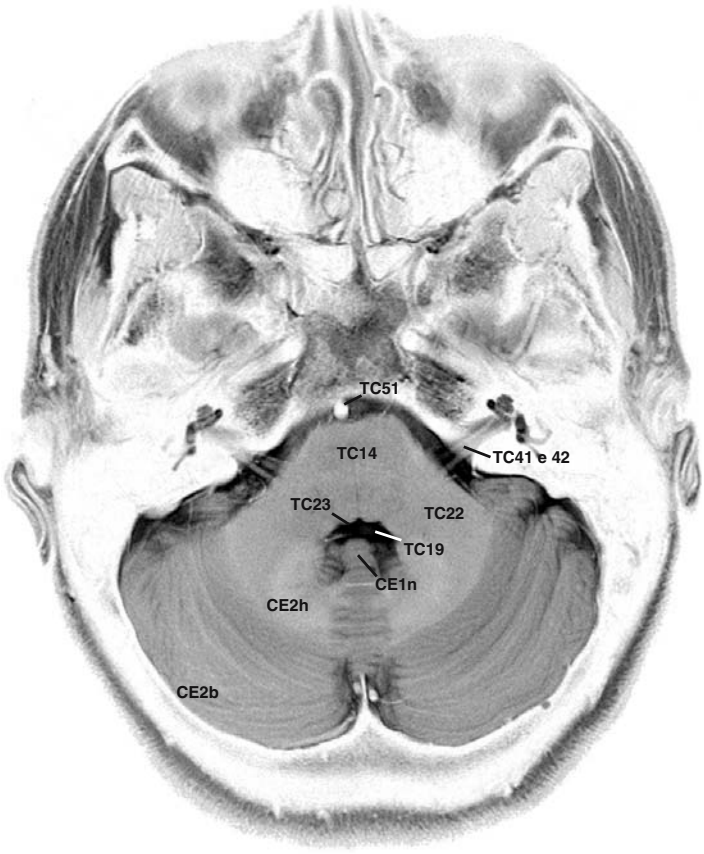

TC47
TC26
TC24
CE2e
TC19
CE2f
CE1e
CE2d



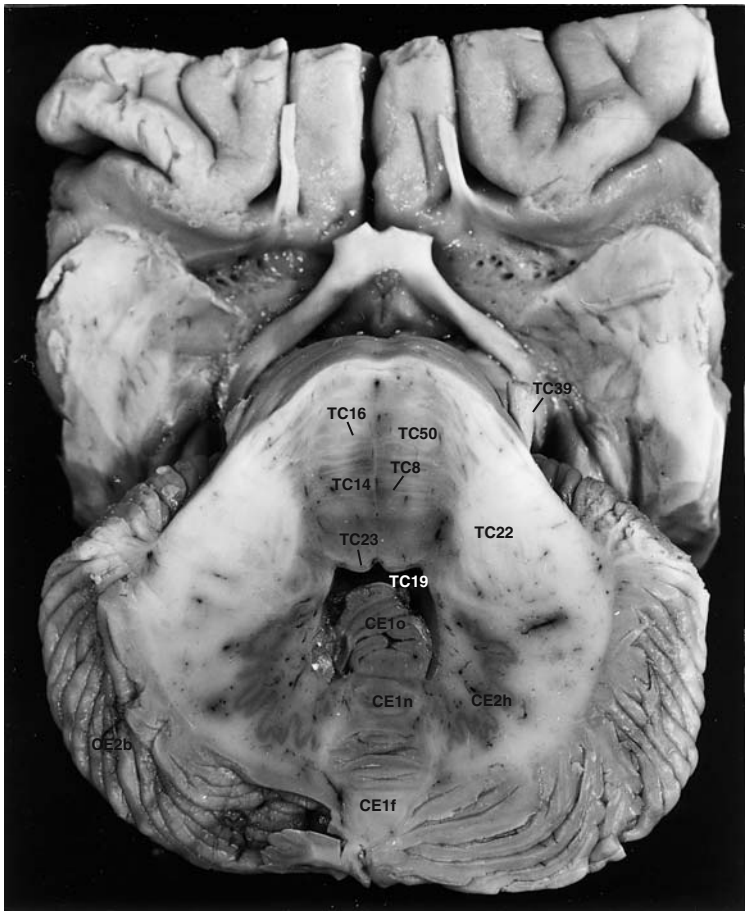

TC14
TC39
TC40
TC30
TC22
TC41
TC42
TC26
TC25
TC24
CE2f
CE2e
CE1n
CE2d

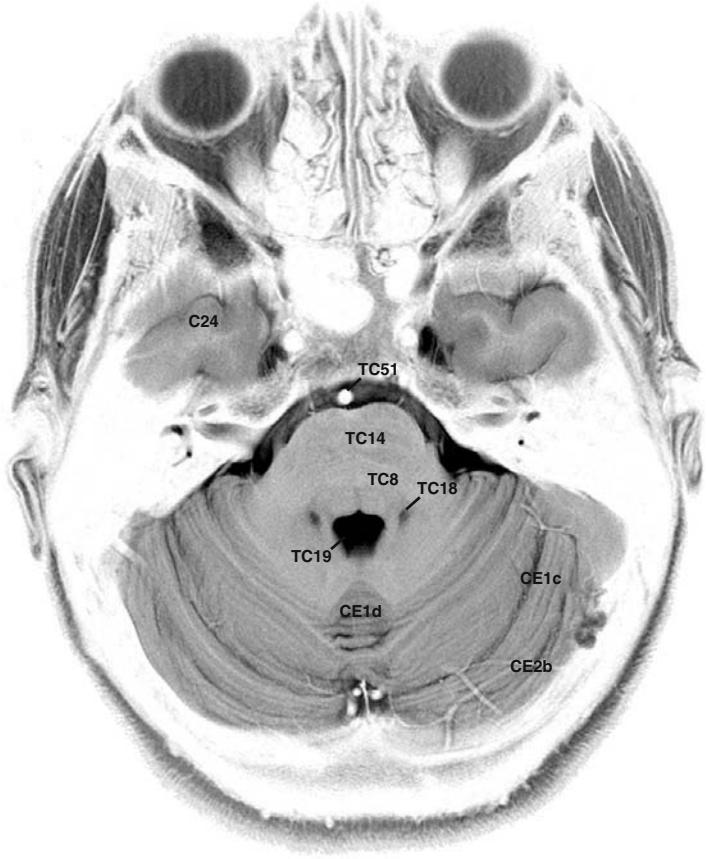

TC14
TC21
CE2f
CE1n
CE2c

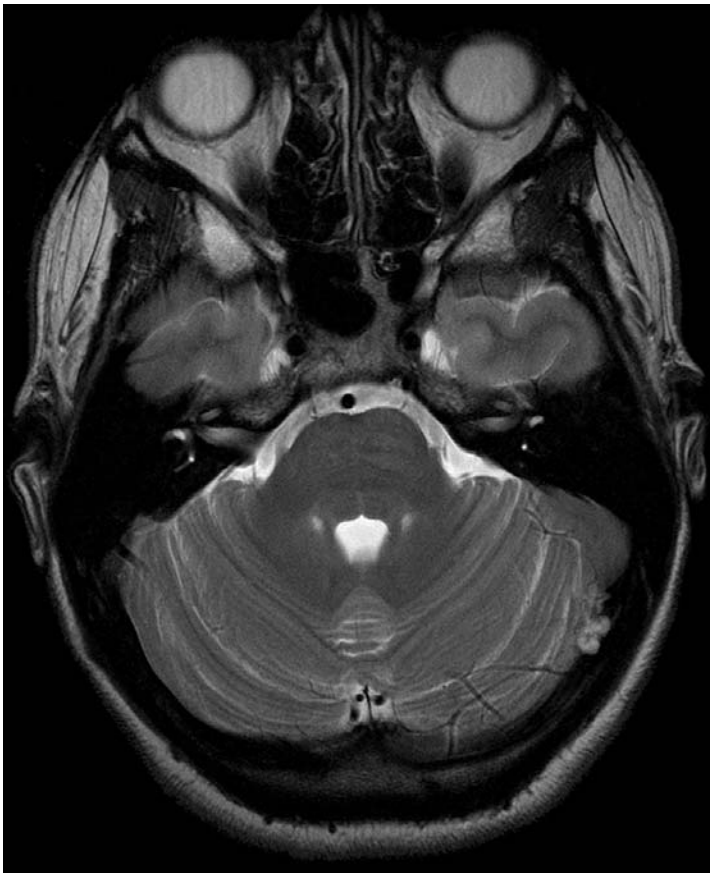
TC39
TC14
TC40
TC22
TC42
TC41
TC25
TC22
TC26
TC8
TC24
TC19
CE2e
CE2f
CE1l
CE2d

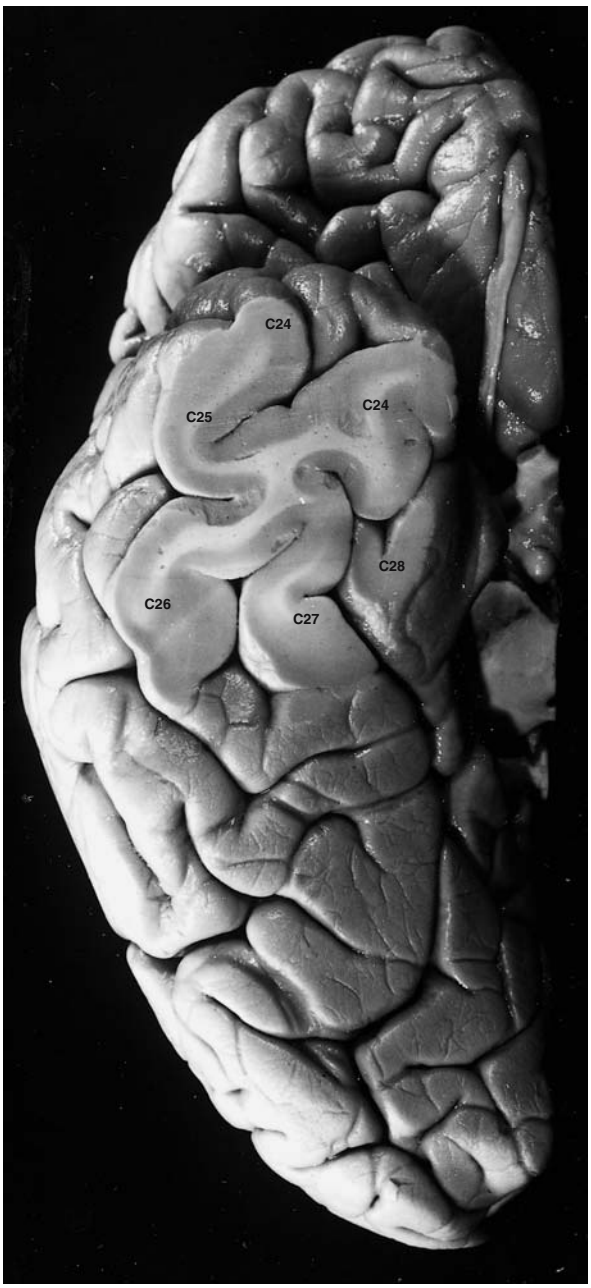

TC51
TC14
TC41 e 42
TC23
TC22
TC19
CE1n
CE2h
CE2b

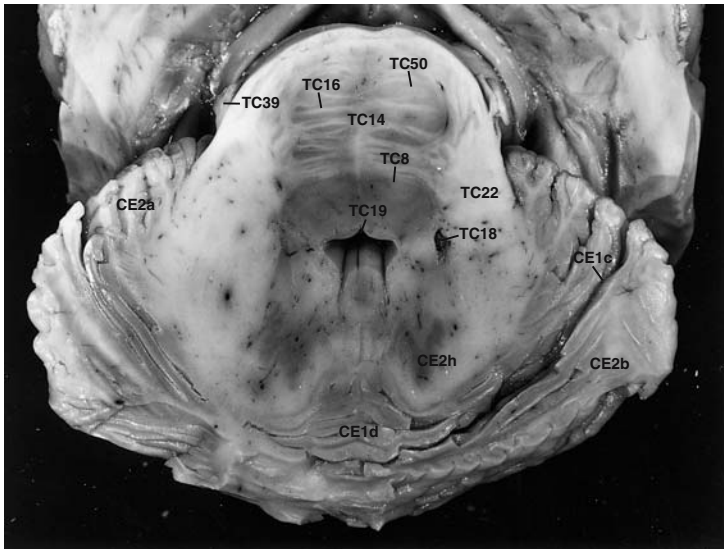
TC14
TC39
TC42
TC41
TC21
CE2g
TC24
TC14
TC22
CE2f
CE2c
CE1n
CE2h

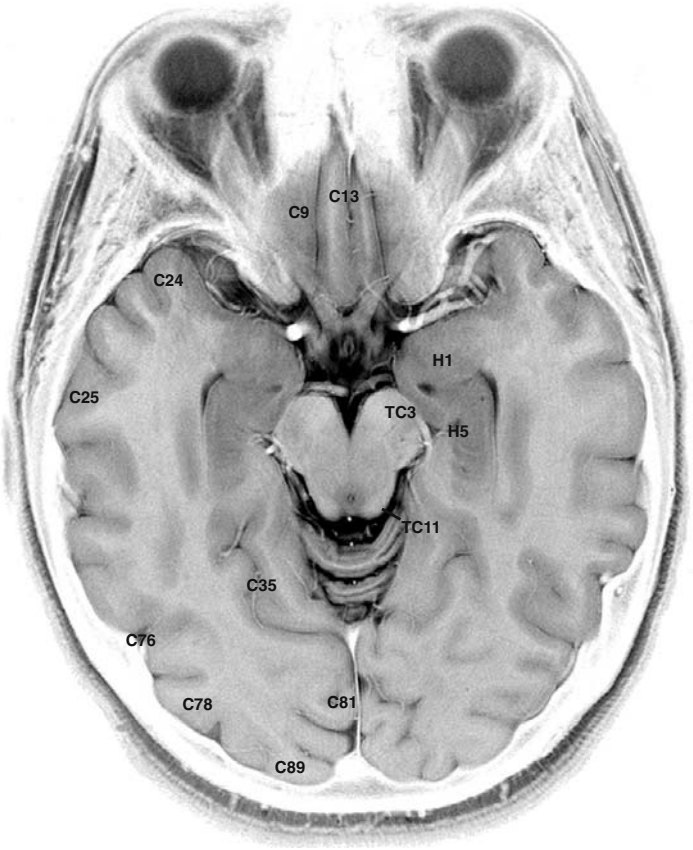

TC39
TC16
TC50
TC8
TC14
TC22
TC23
TC19
CE1o
CE1n
CE2h
CE2b
CE1f

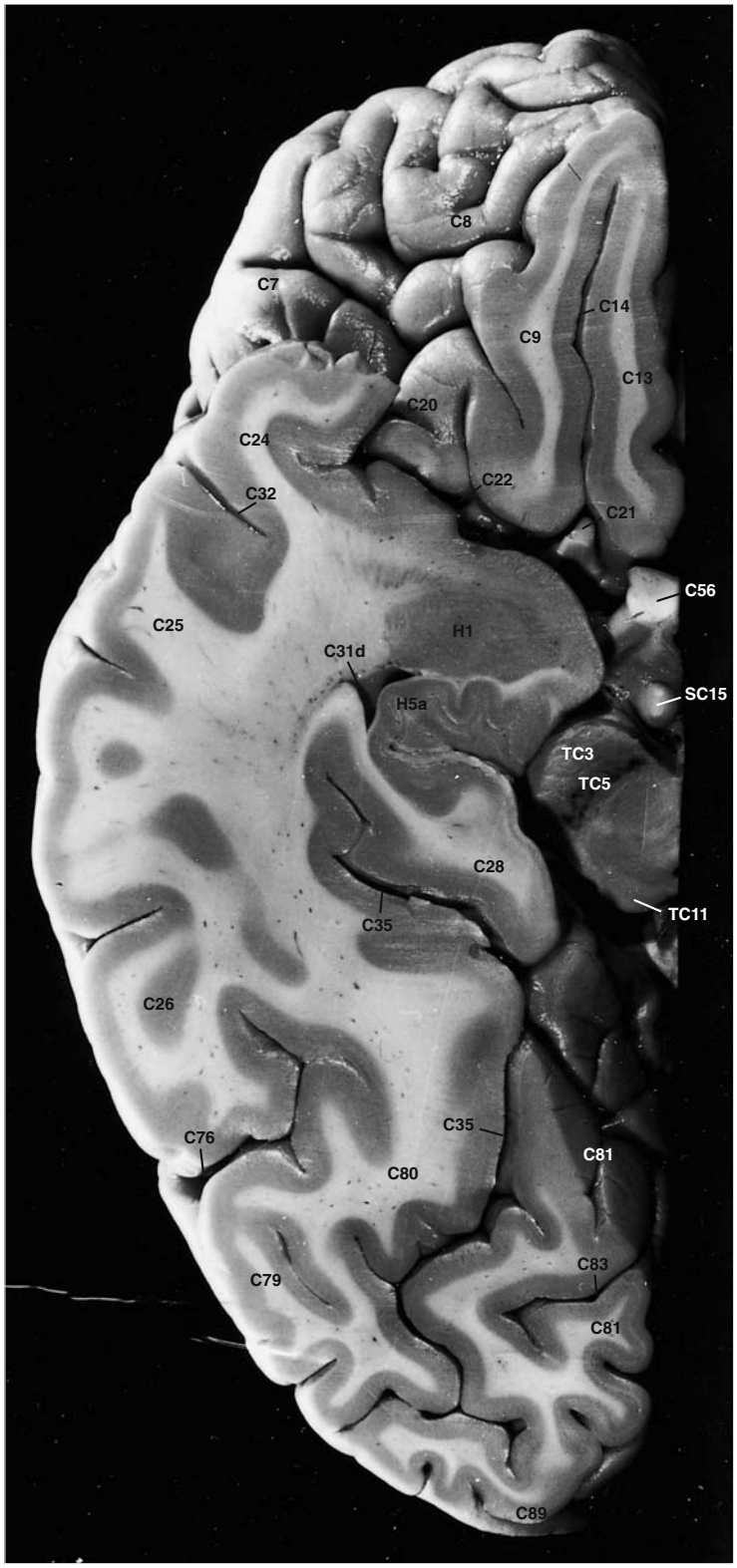

C24
TC51
TC14
TC8
TC18
TC19
CE1c
CE1d
CE2b

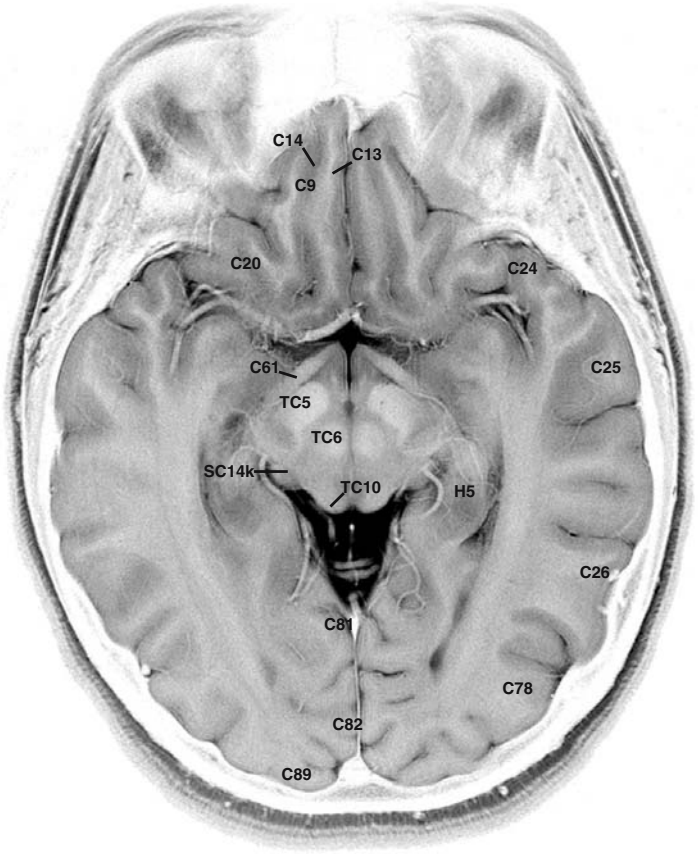


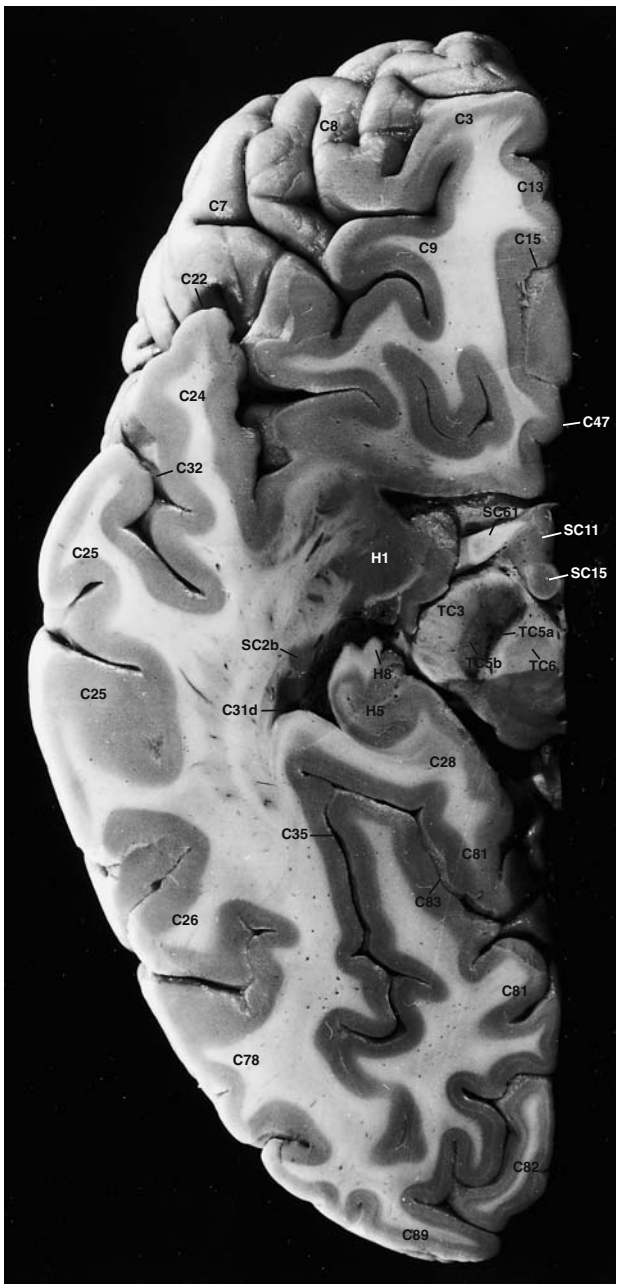

C24
C25
C24
C28
C26
C27

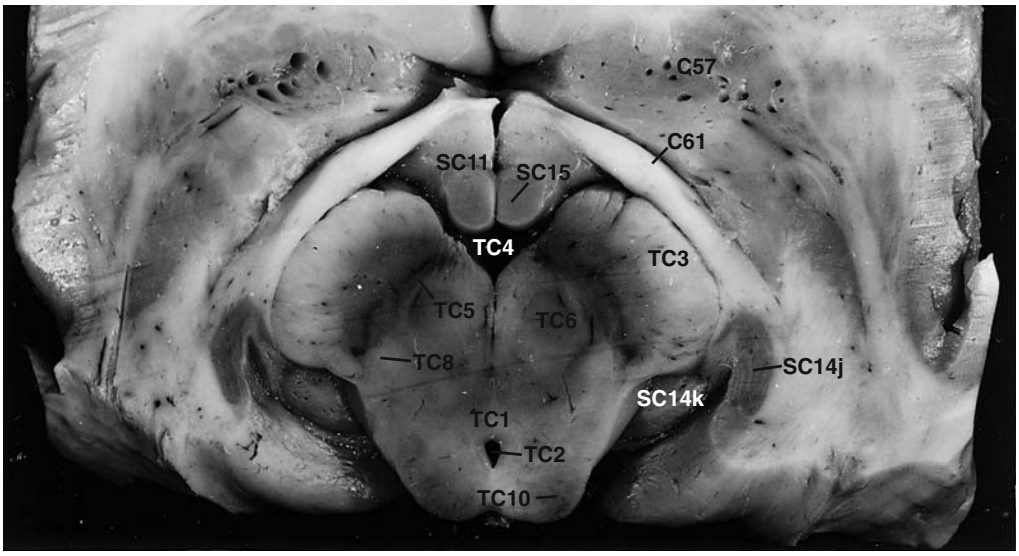

TC50
TC16
TC39
TC14
TC8
TC22
CE2a
TC19
TC18
CE1c
CE2h
CE2b
CE1d

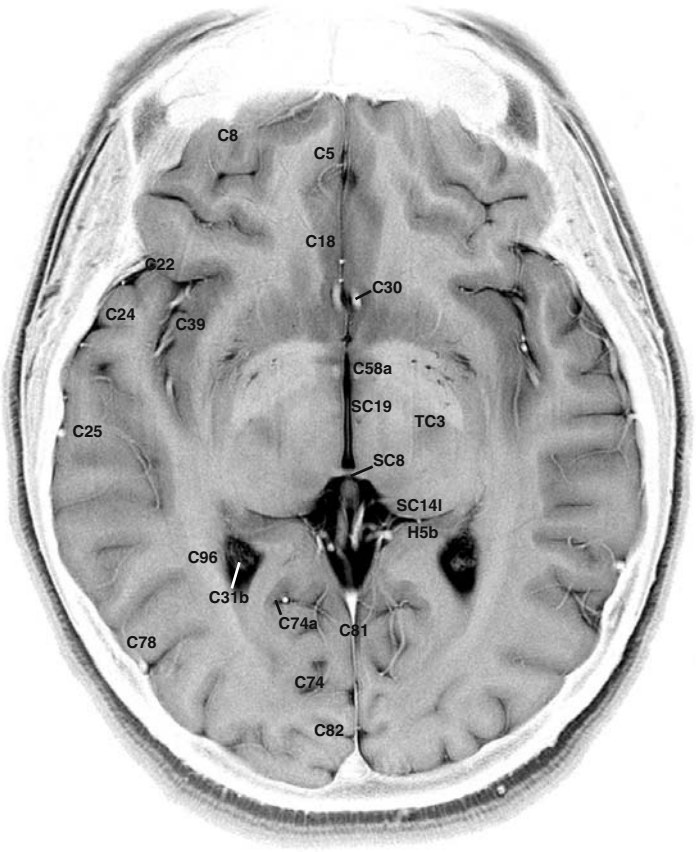

C13
C9
C24
H1
C25
TC3
H5
TC11
C35
C76
C78
C81
C89

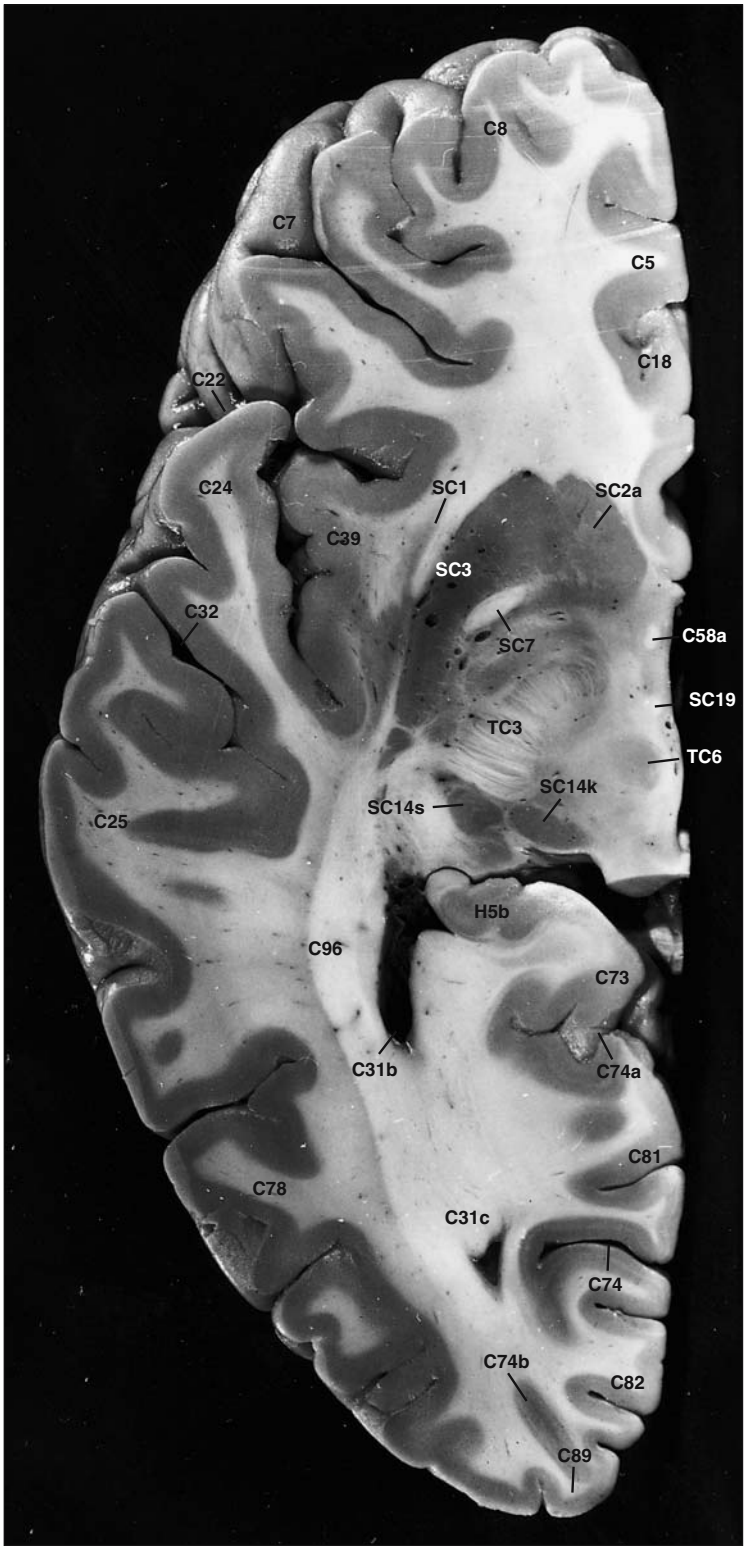

C8
C7
C14
C9
C13
C20
C24
C22
C32
C21
C56
C25
H1
C31d
SC15
H5a
TC3
TC5
C28
TC11
C35
C26
C35
C76
C81
C80
C83
C79
C81
C89

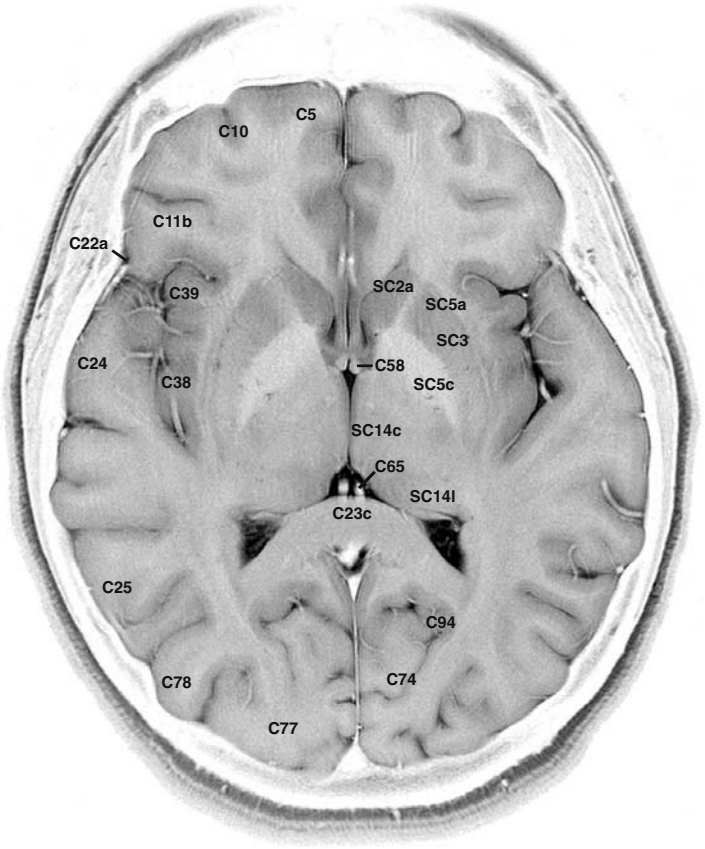

C14
C13
C9
C20
C24
C61
C25
TC5
TC6
SC14k
TC10
H5
C26
C81
C78
C82
C89

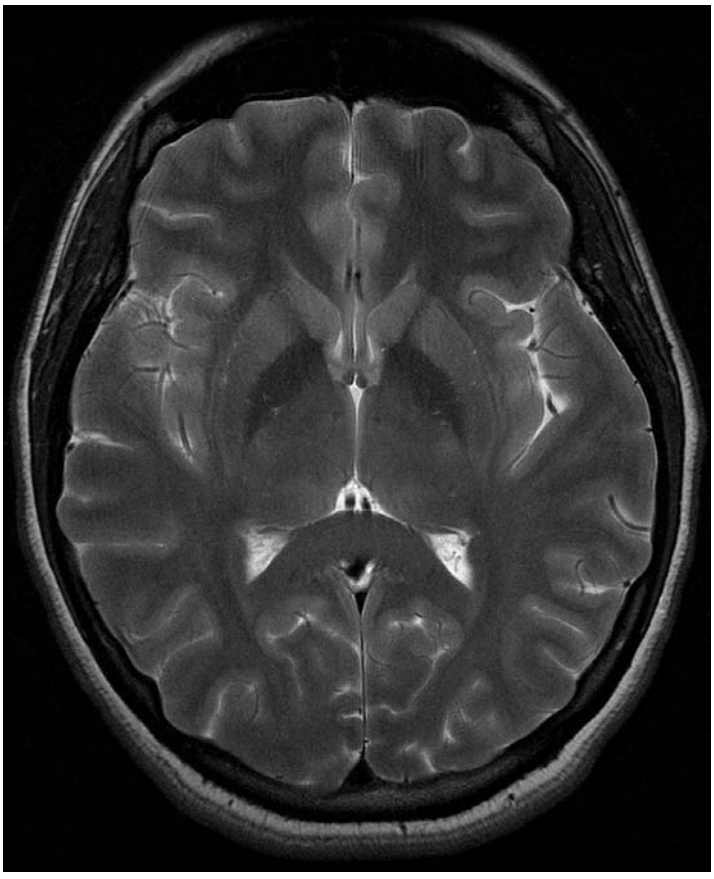

C8
C3
C13
C7
C9
C15
C22
C24
C47
C32
SC61
SC11
C25
H1
SC15
TC3
TC5a
SC2b
TC5b
TC6
H8
C25
C31d
H5
C28
C35
C81
C83
C26
C81
C78
C82
C89

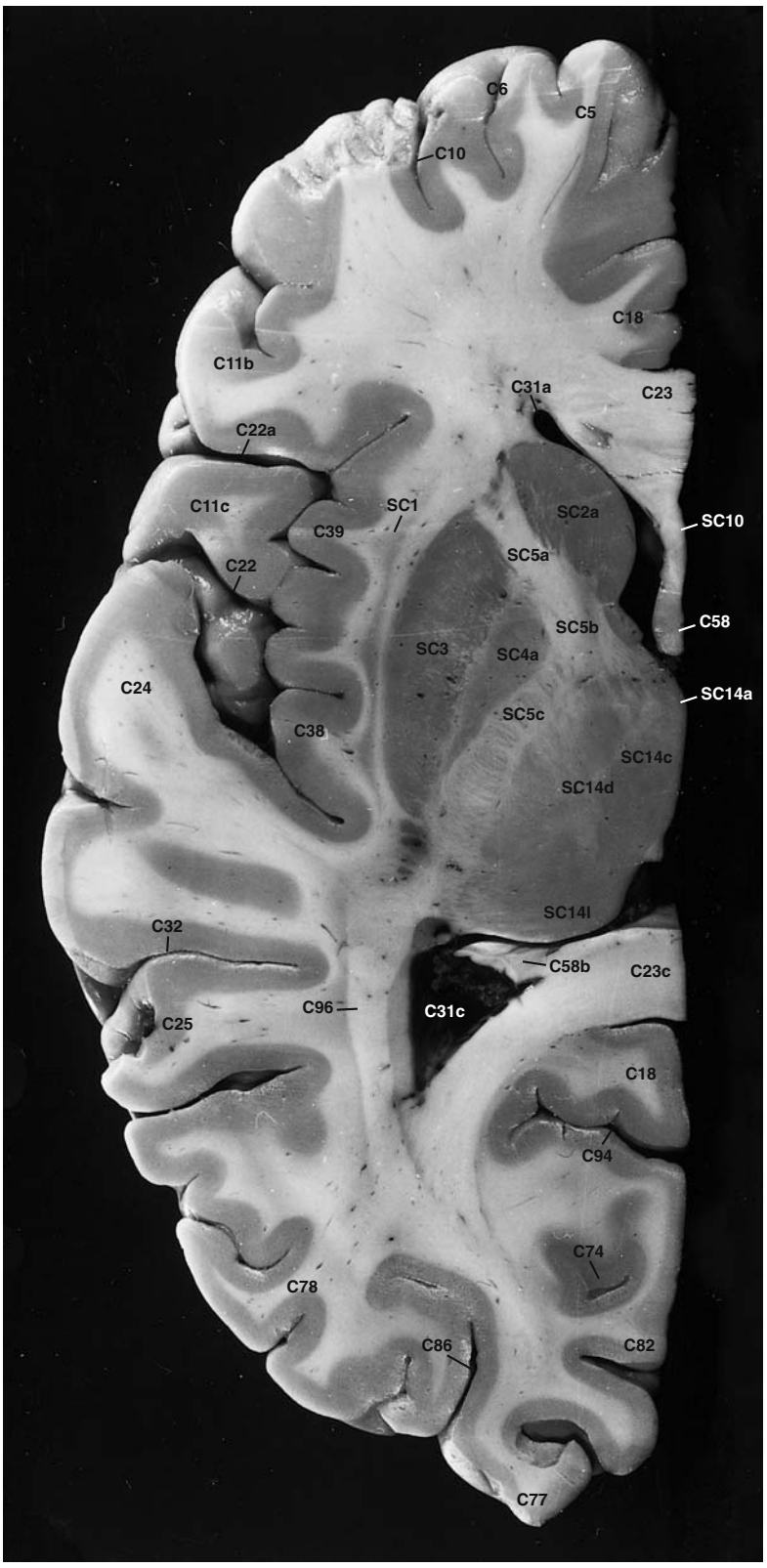

C57
C61
SC11
SC15
TC4
TC3
TC5
TC6
TC8
SC14j
SC14k
TC1
TC2
TC10

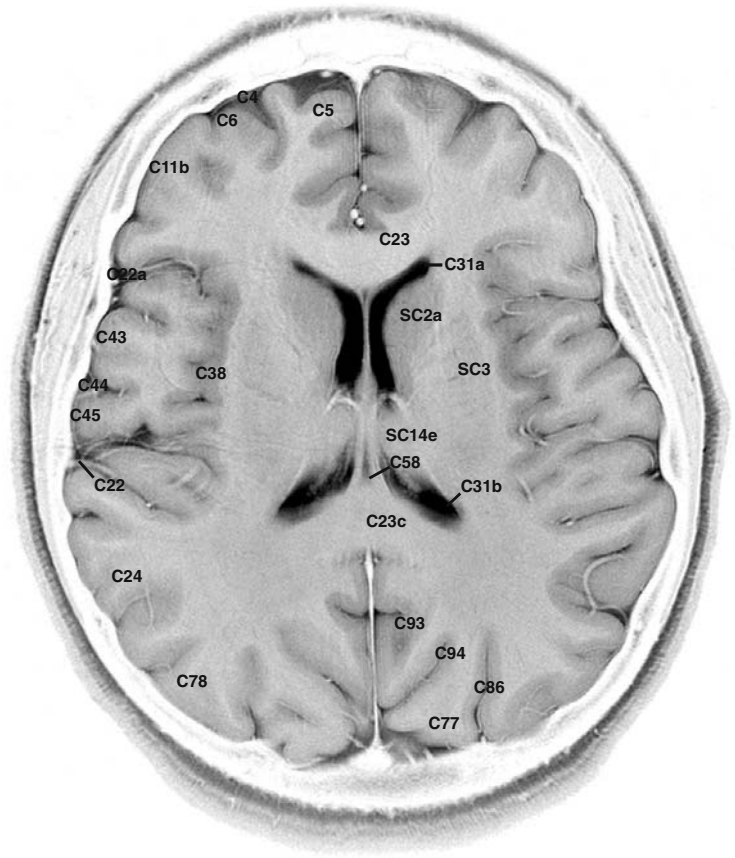

C8
C5
C18
C22
C30
C24
C39
C58a
SC19
TC3
C25
SC8
SC14l
H5b
C96
C31b
C74a
C81
C78
C74
C82

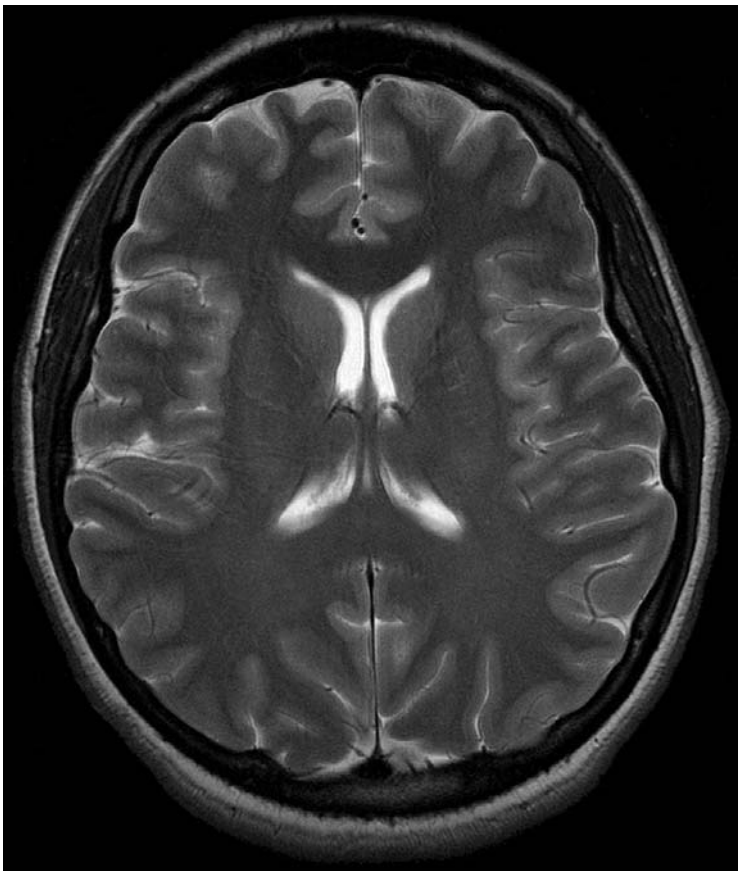

C8
C7
C5
C18
C22
C24
SC1
SC2a
C39
SC3
C32
SC7
C58a
SC19
TC3
TC6
SC14k
SC14s
C25
H5b
C96
C73
C31b
C74a
C81
C78
C31c
C74
C74b
C82
C89

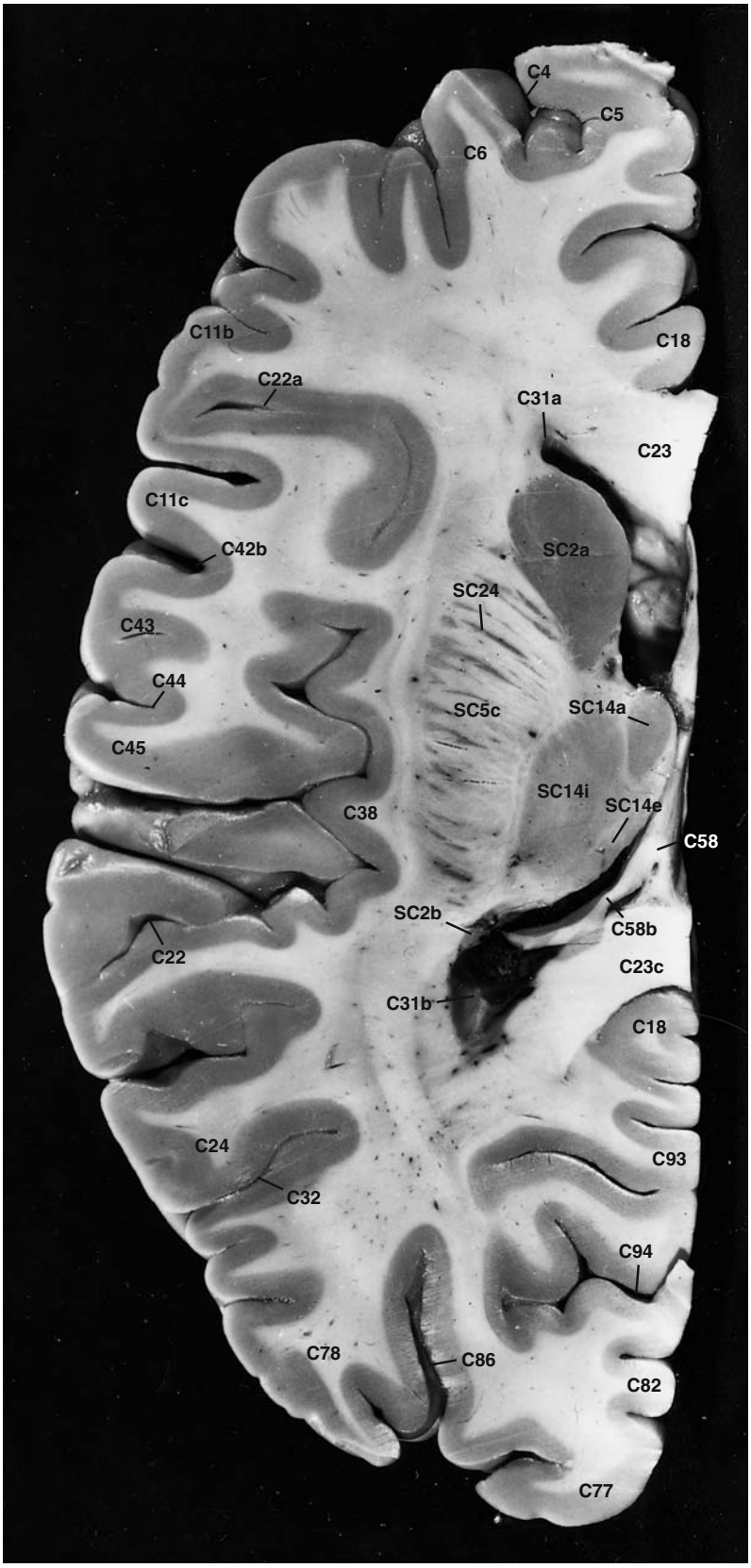

C5
C10
C11b
C22a
C39
SC2a
SC5a
SC3
C24
C58
C38
SC5c
SC14c
C65
SC14l
C23c
C25
C94
C78
C74
C77

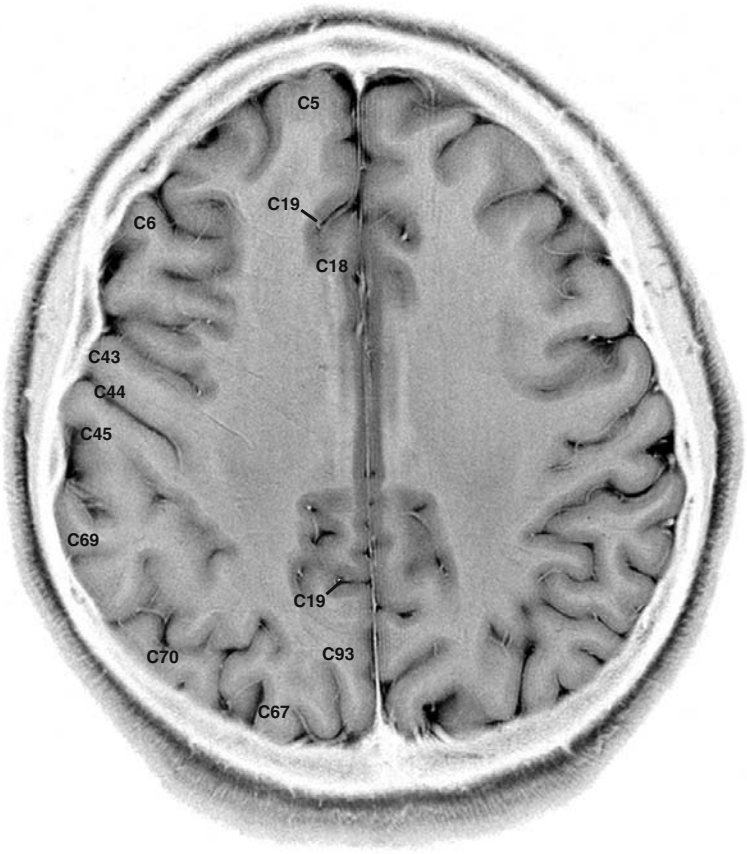


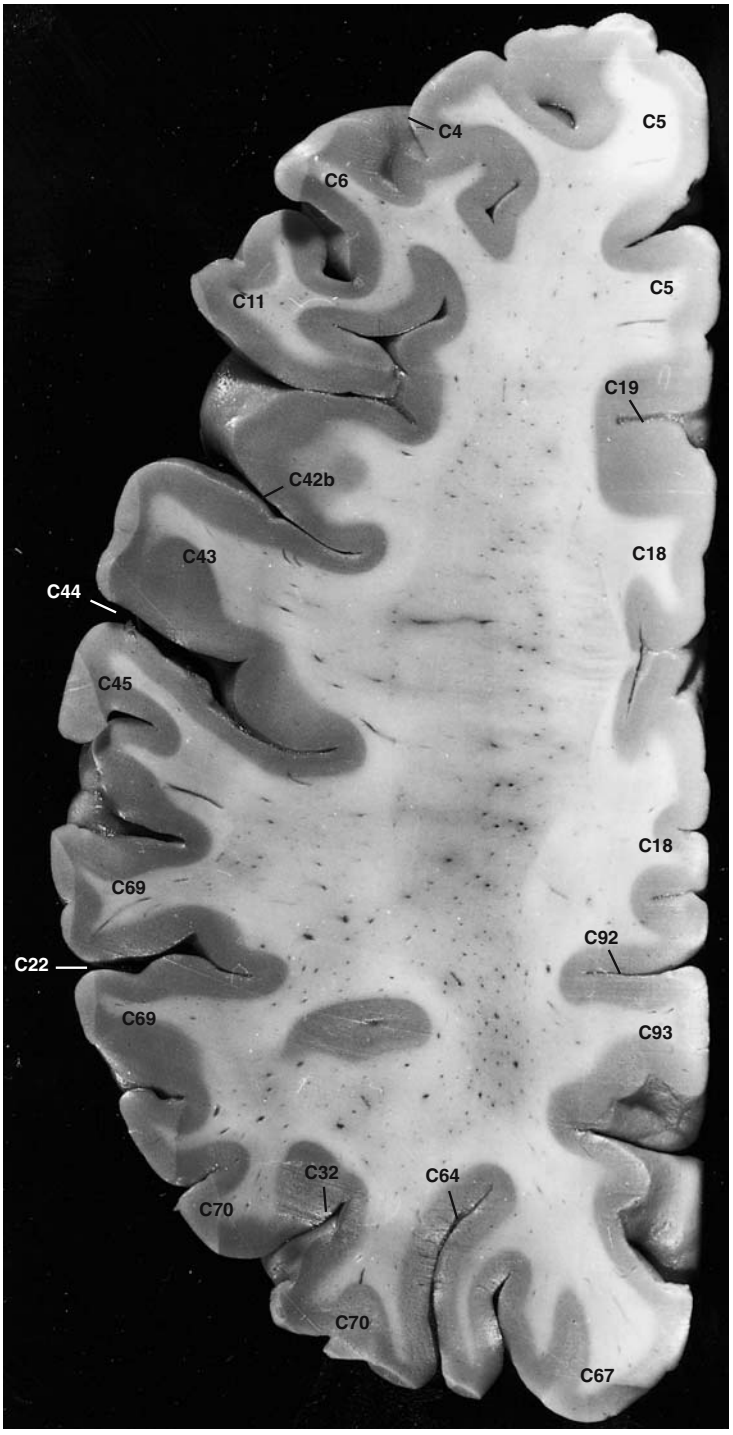

C6
C5
C10
C18
C11b
C31a
C23
C22a
C11c
SC1
SC2a
SC10
C39
SC5a
C22
SC5b
C58
SC3
SC4a
C24
SC14a
SC5c
C38
SC14c
SC14d
SC14l
C32
C58b
C23c
C96
C31c
C25
C18
C94
C74
C78
C86
C82
C77

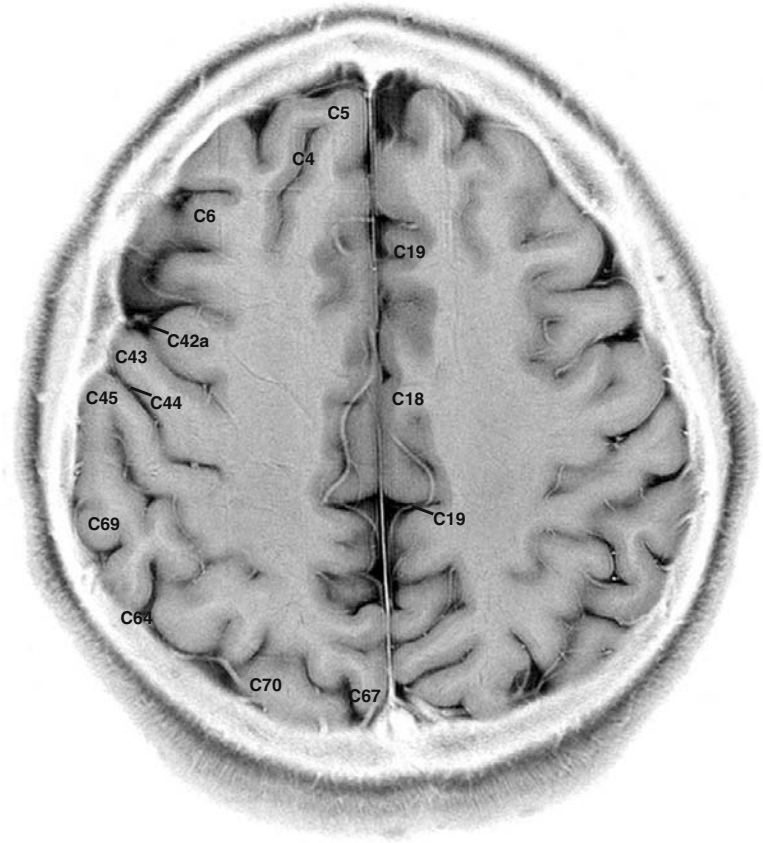

C4
C6
C5
C11b
C23
C31a
C22a
SC2a
C43
C38
SC3
C44
C45
SC14e
C58
C22
C31b
C23c
C24
C93
C94
C78
C86
C77

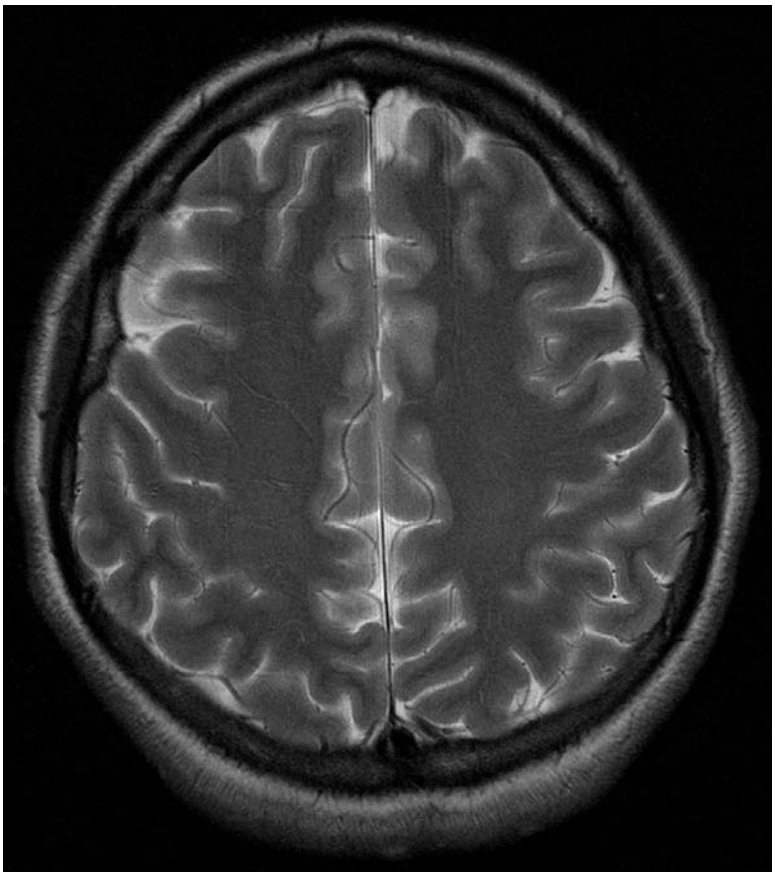


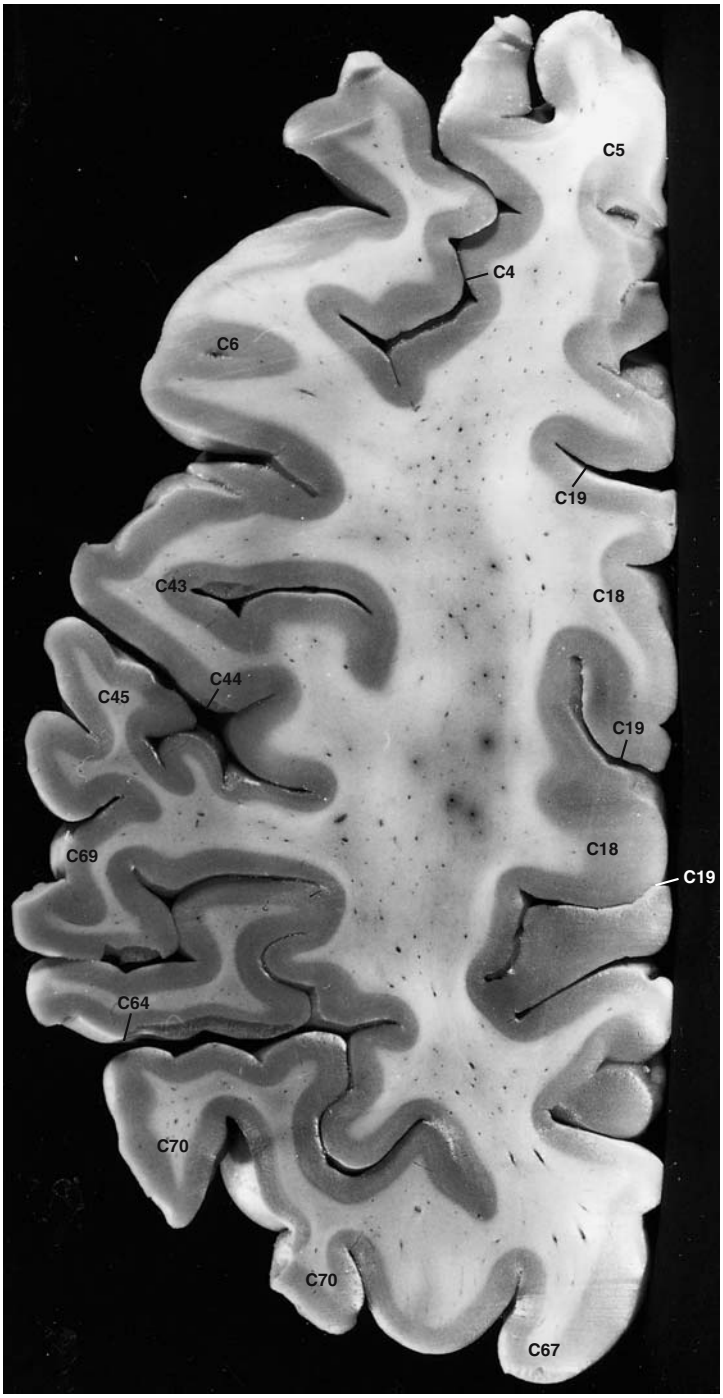

C4
C5
C6
C11b
C18
C22a
C31a
C23
C11c
C42b
SC2a
SC24
C43
C44
SC5c
SC14a
C45
SC14i
SC14e
C38
C58
SC2b
C58b
C22
C23c
C31b
C18
C24
C93
C32
C94
C78
C86
C82
C77

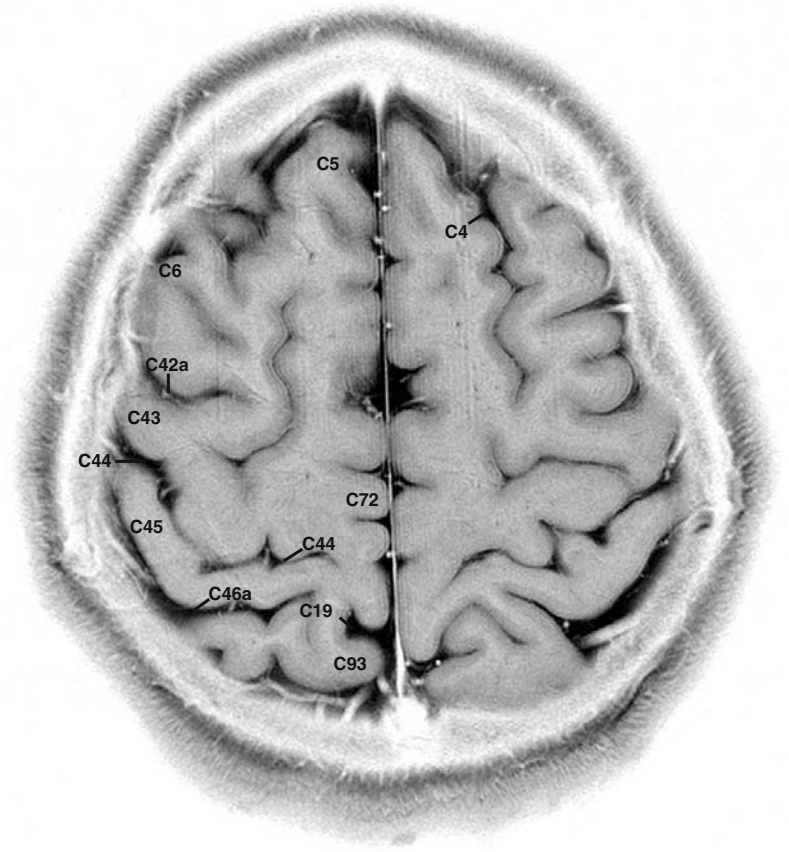

C5
C19
C6
C18
C43
C44
C45
C69
C19
C70
C93
C67

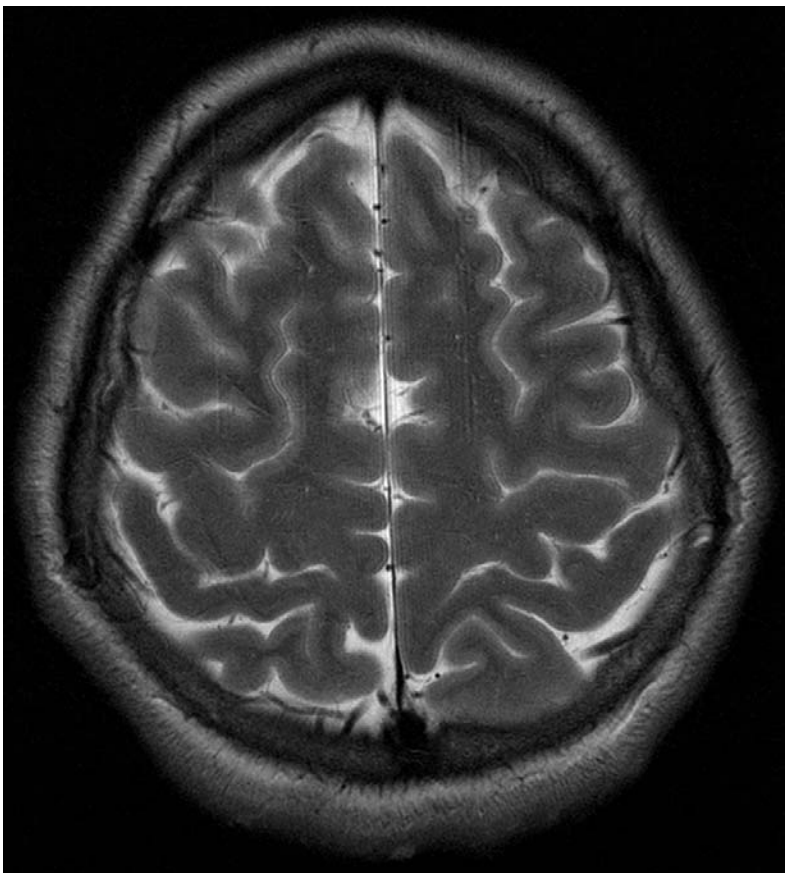

C4
C5
C6
C11
C5
C19
C42b
C43
C18
C44
C45
C18
C69
C92
C22
C69
C93
C32
C64
C70
C70
C67

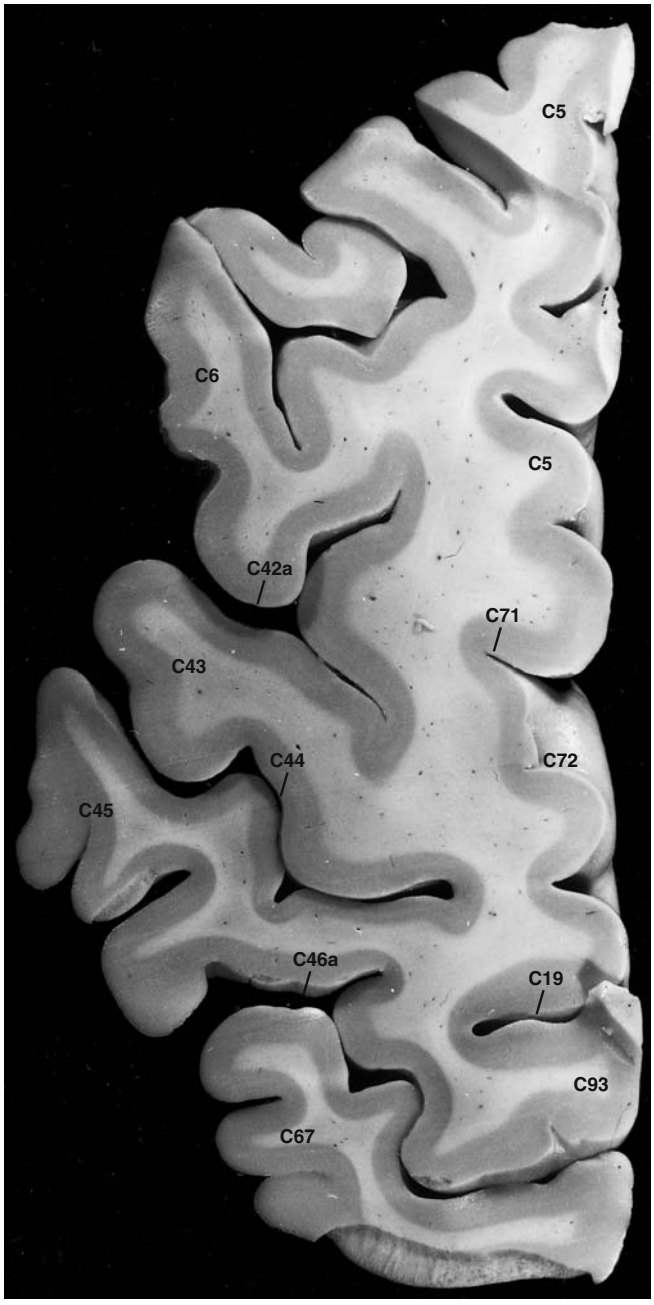

C5
C4
C6
C19
C42a
C43
C45
C44
C18
C19
C69
C64
C70
C67




C5
C4
C6
C19
C43
C18
C44
C45
C19
C18
C69
C19
C64
C70
C70
C67

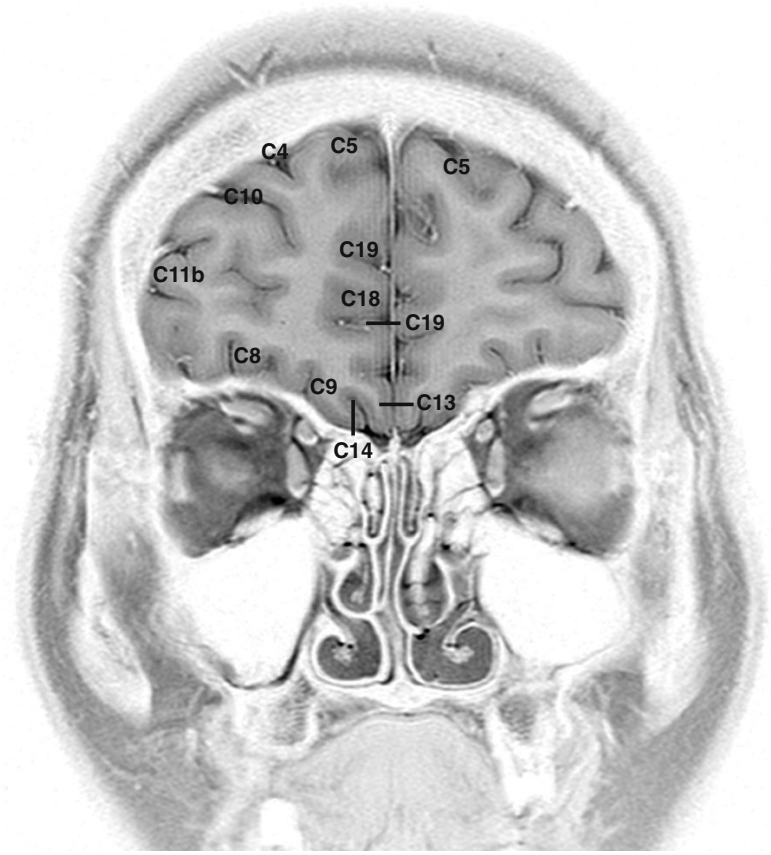

C5
C4
C6
C42a
C43
C44
C72
C45
C44
C46a
C19
C93

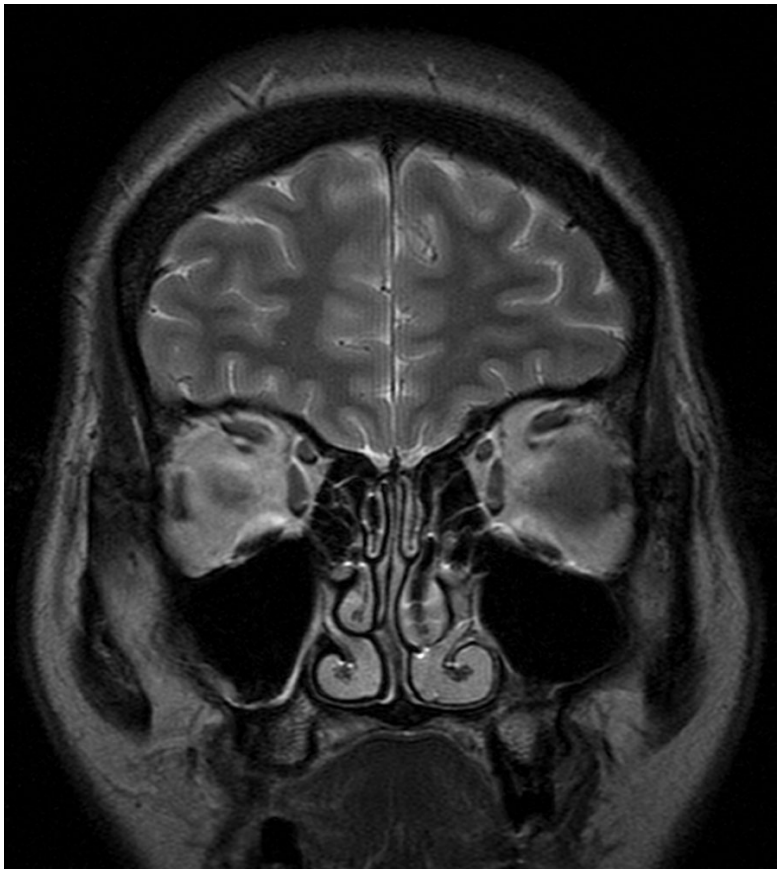


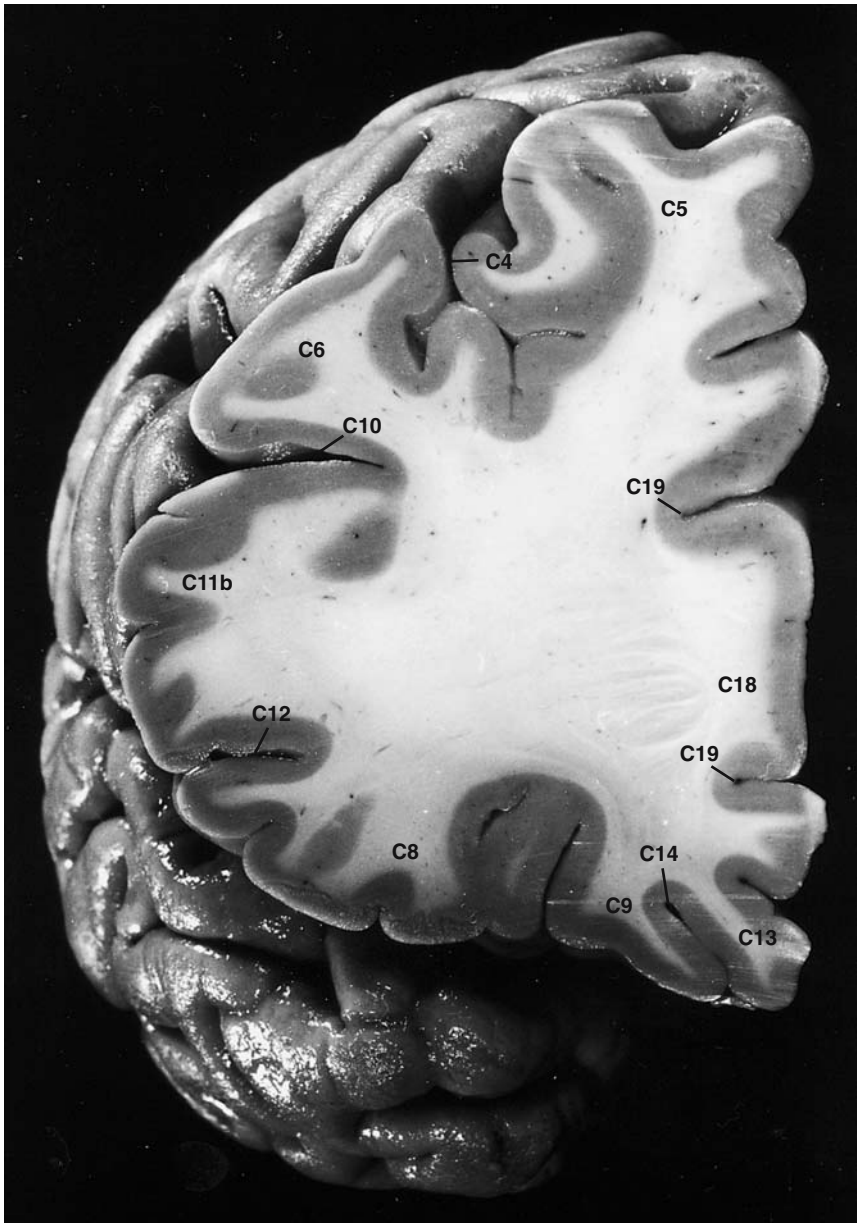

C5
C6
C5
C42a
C71
C43
C44
C72
C45
C46a
C19
C93
C67

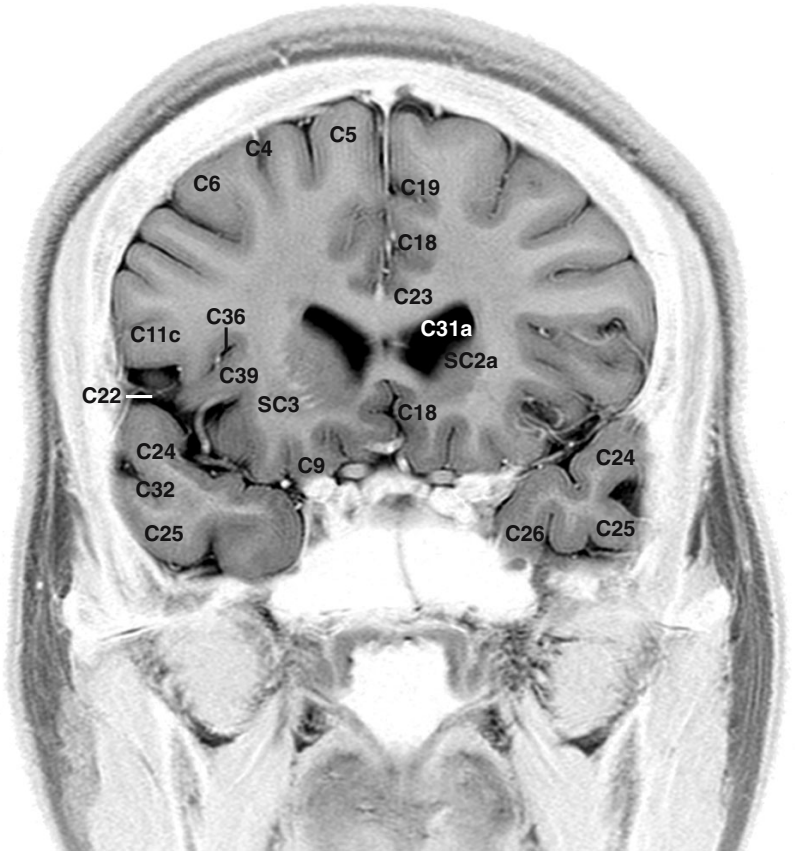
CORONAL CUTS

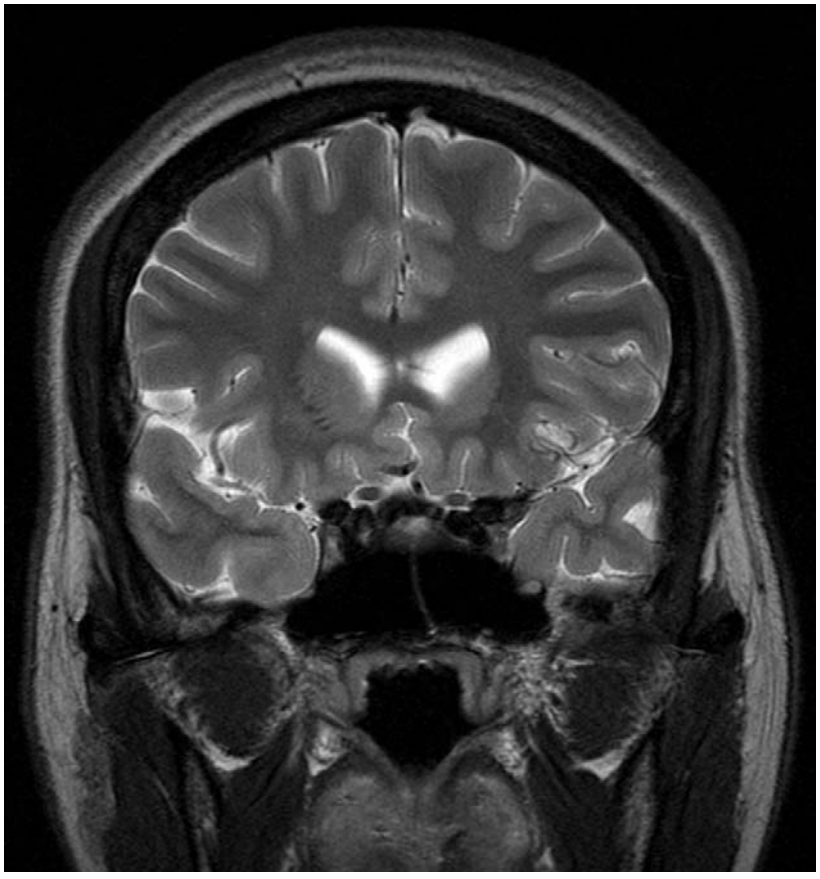
In the following pages (62–83), high definition T2-W FSE coronal MR cuts (left) are compared with “traditional” anatomical cuts (right).
See the jacket flap for anatomical references.

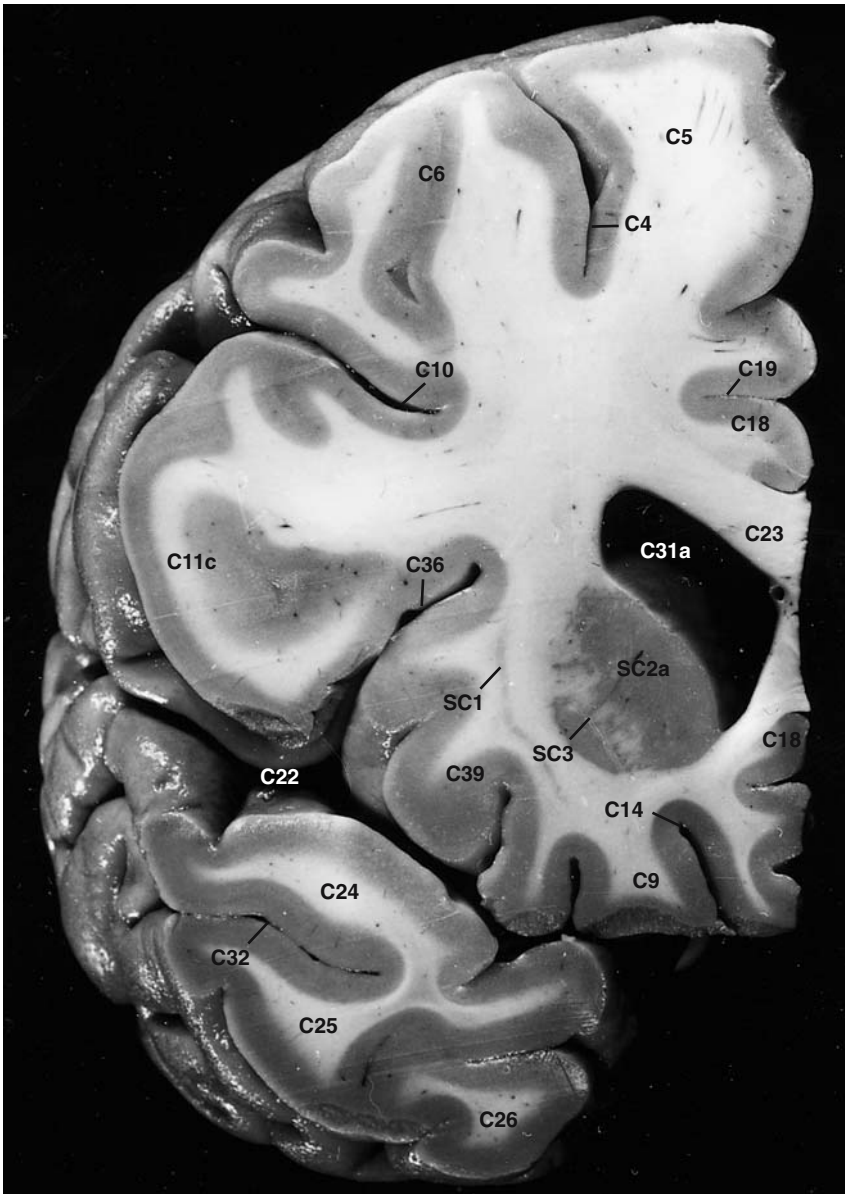

C4
C5
C5
C10
C19
C11b
C18
C19
C8
C9
C13
C14

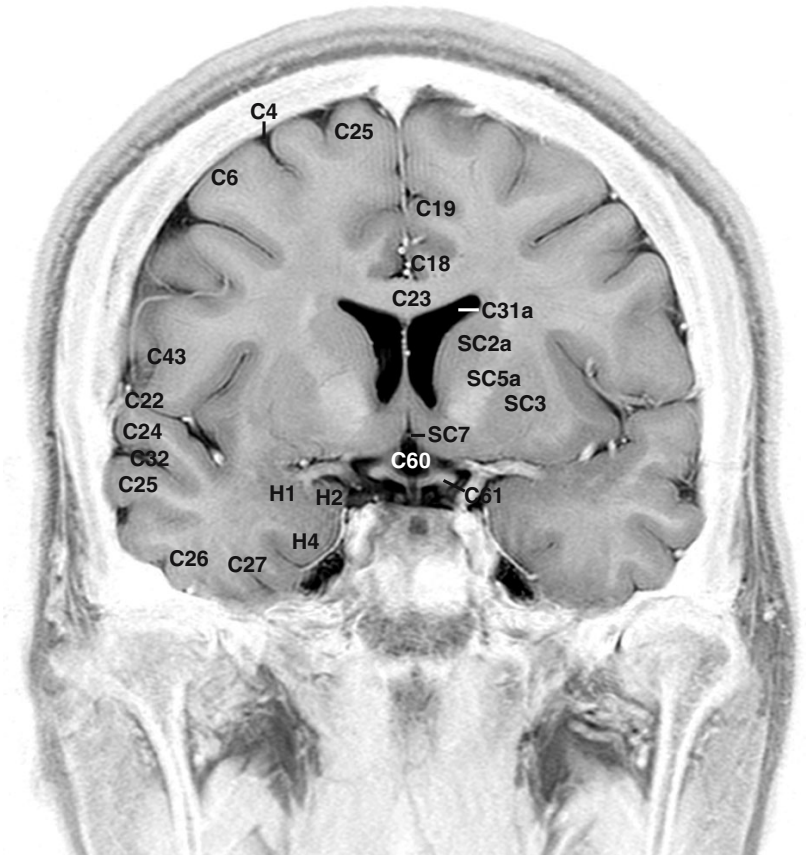


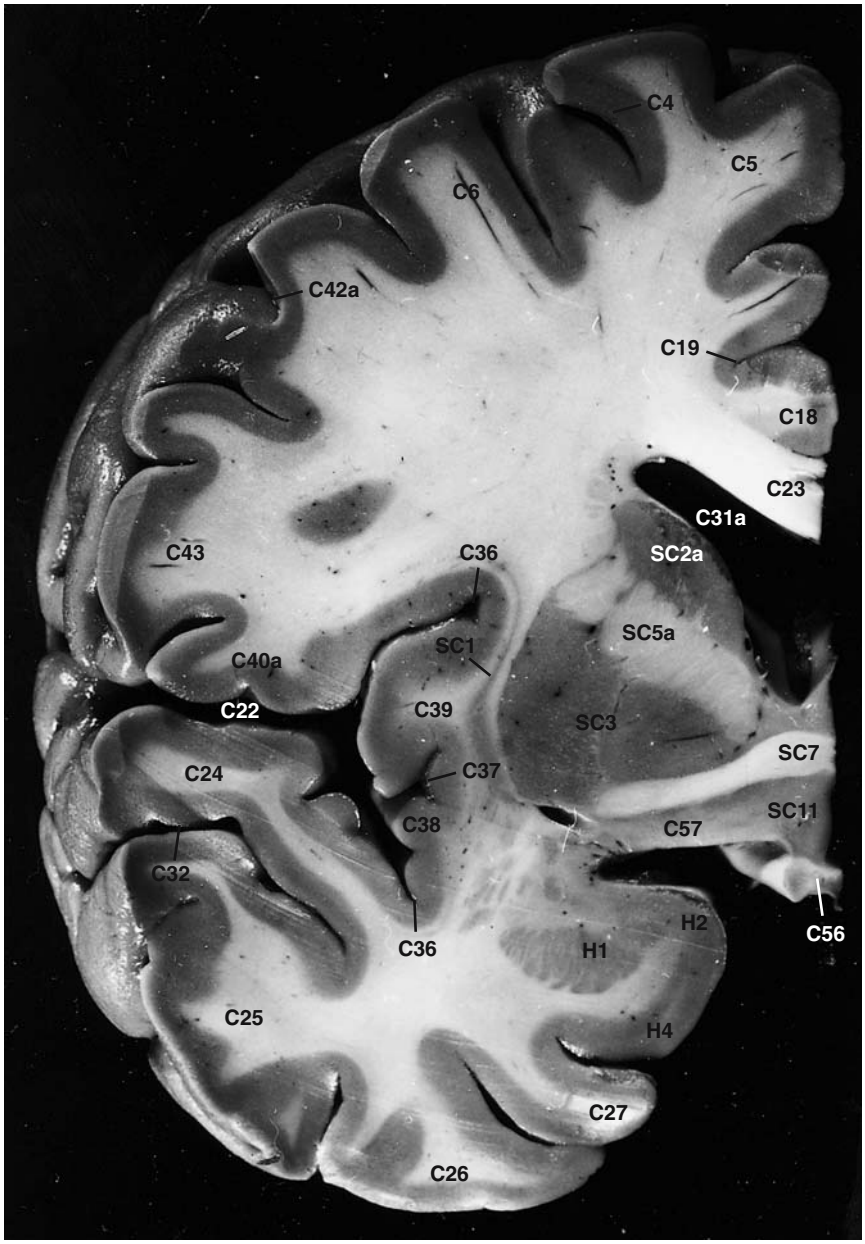

C5
C4
C6
C10
C19
C11b
C18
C12
C19
C8
C14
C9
C13

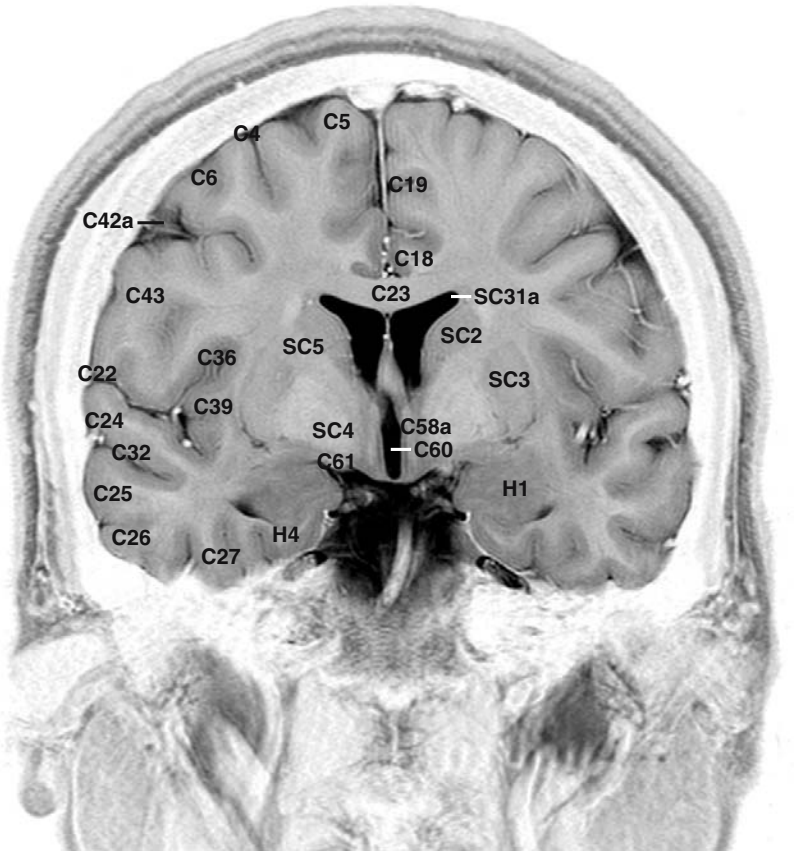

C4
C5
C6
C19
C18
C23
C36
C31a
C11c
SC2a
C39
C22
SC3
C18
C24
C9
C24
C32
C25
C26
C25

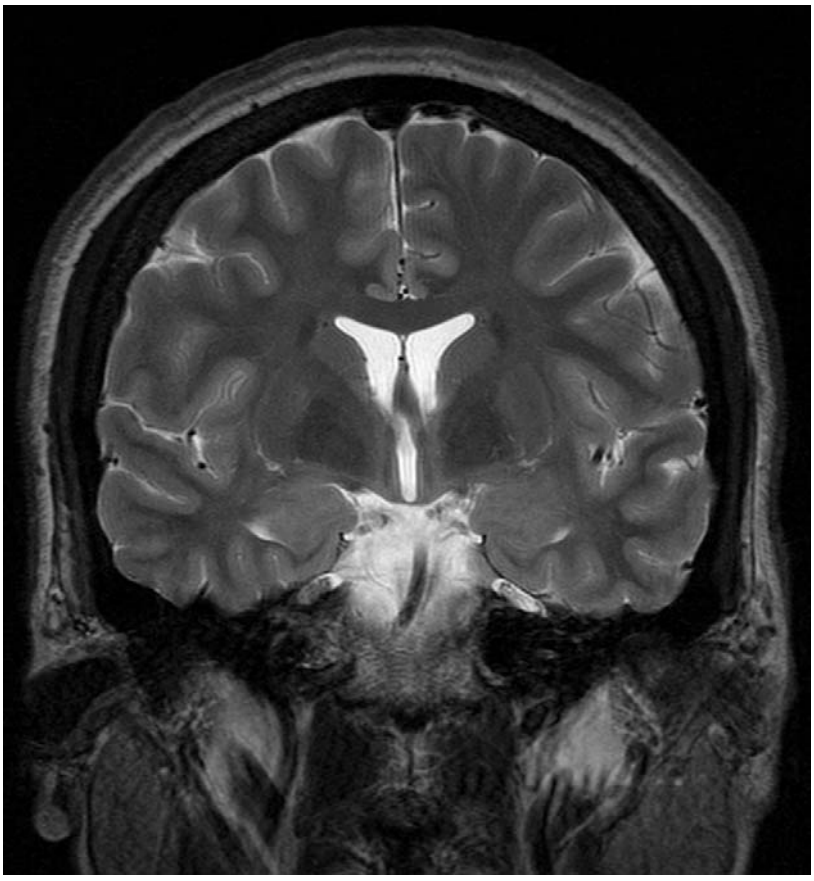


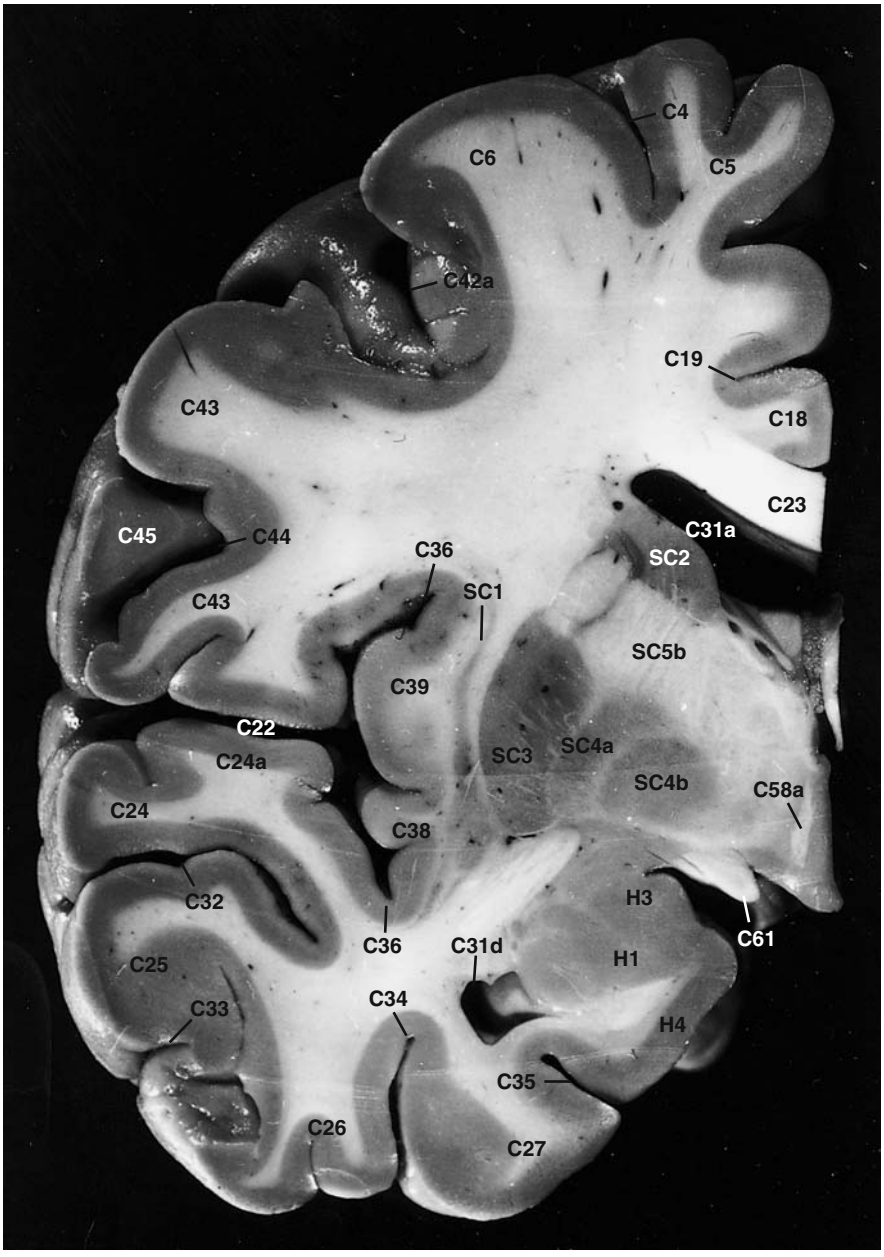

C5
C6
C4
C10
C19
C18
C23
C31a
C11c
C36
SC2a
SC1
C18
SC3
C22
C39
C14
C9
C24
C32
C25
C26

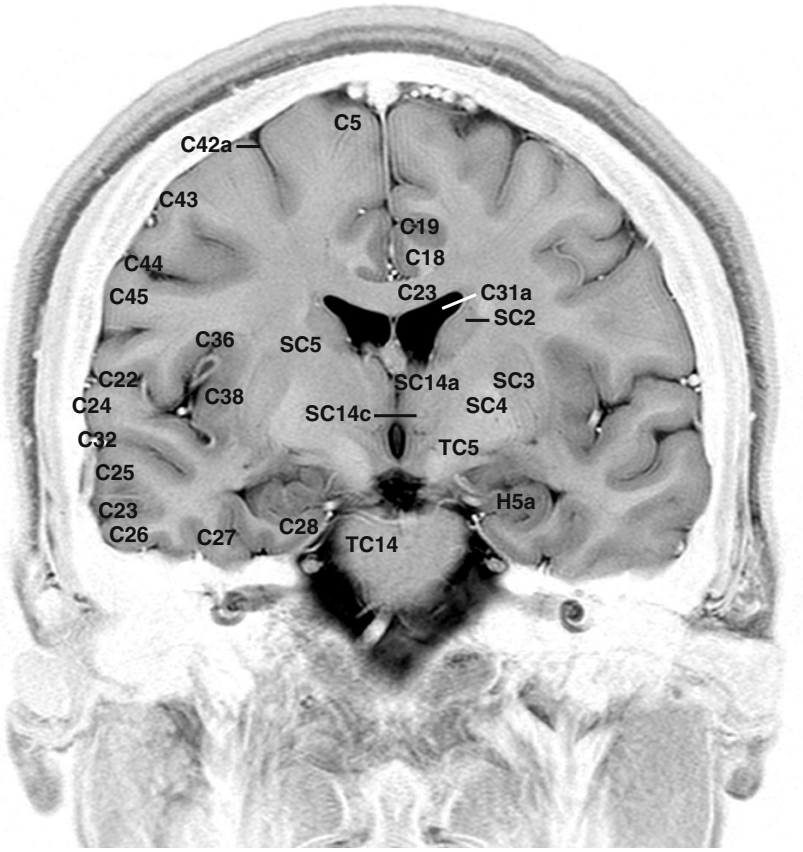

C4
C25
C6
C19
C18
C23
C31a
SC2a
C43
SC5a
SC3
C22
C24
SC7
C32
C60
C25
H1
H2
C61
H4
C26
C27

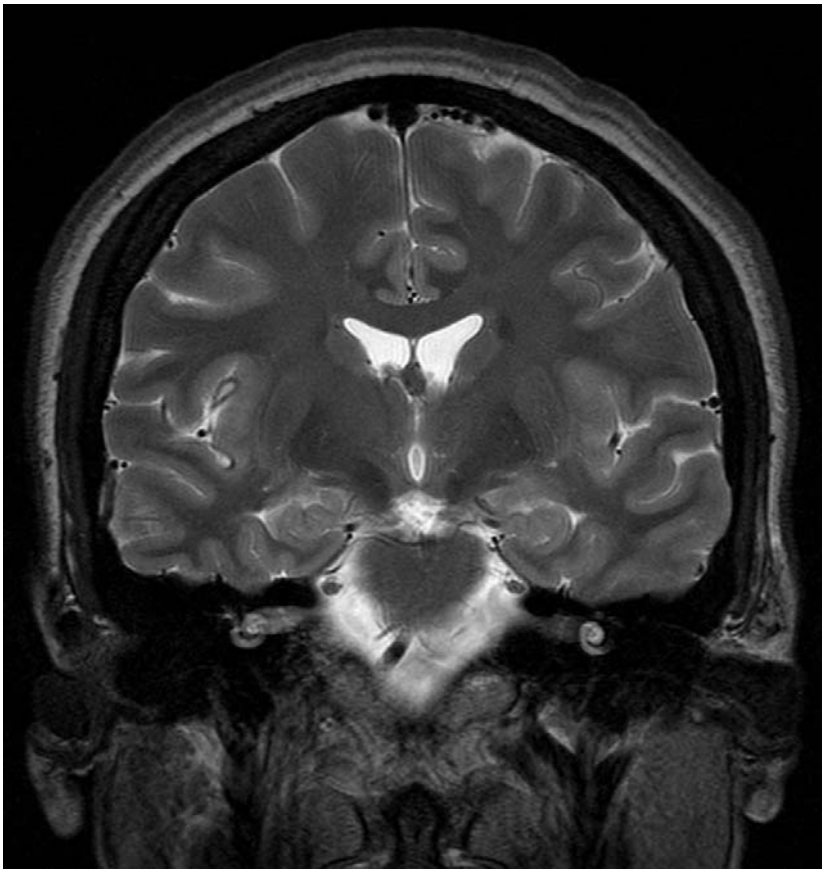

C4
C5
C6
C42a
C19
C18
C23
C31a
SC2a
C43
C36
SC5a
SC1
C40a
C22
C39
SC3
SC7
C24
C37
SC11
C38
C57
C32
H2
C56
C36
H1
C25
H4
C27
C26

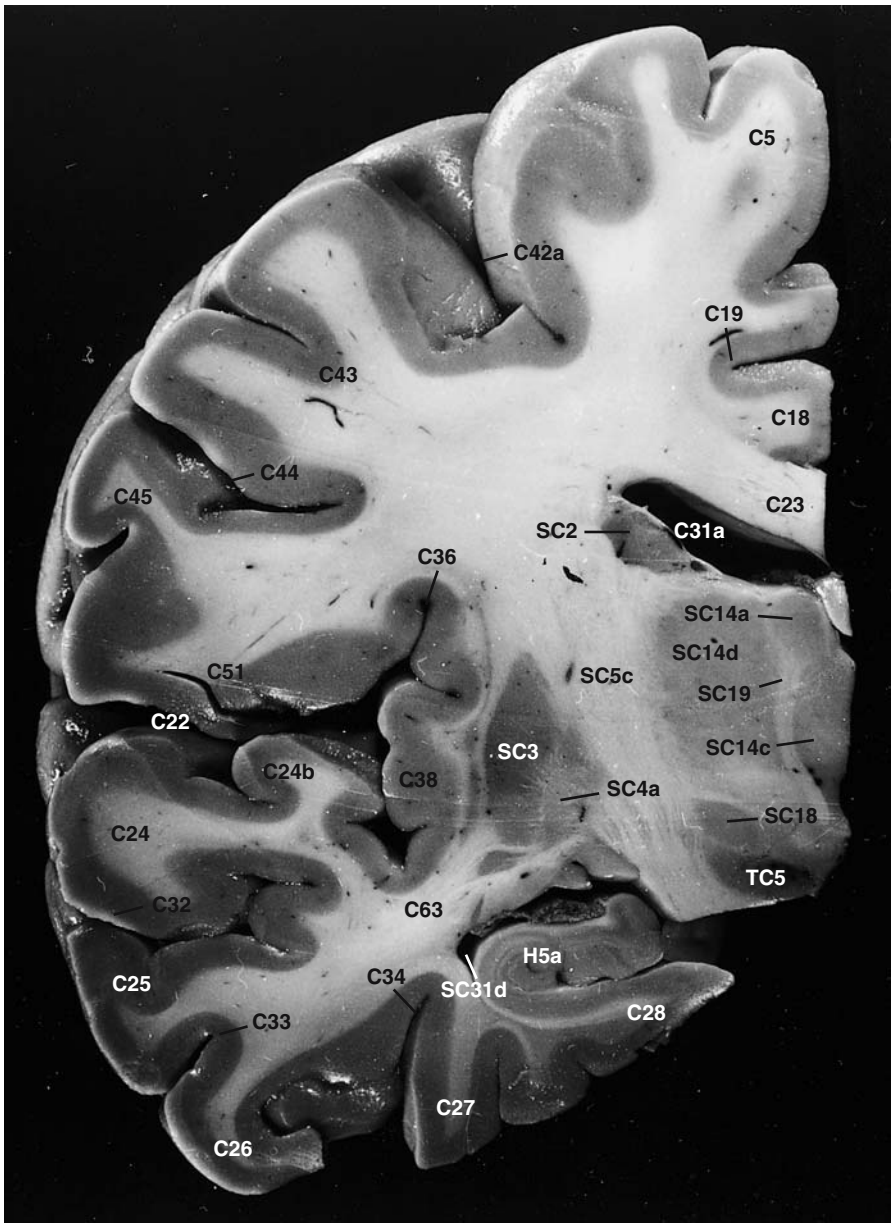

C4
C5
C6
C19
C42a
C18
C43
C23
SC31a
SC5
SC2
C36
C22
SC3
C39
C24
SC4
C58a
C32
C61
C60
H1
C25
C26
H4
C27

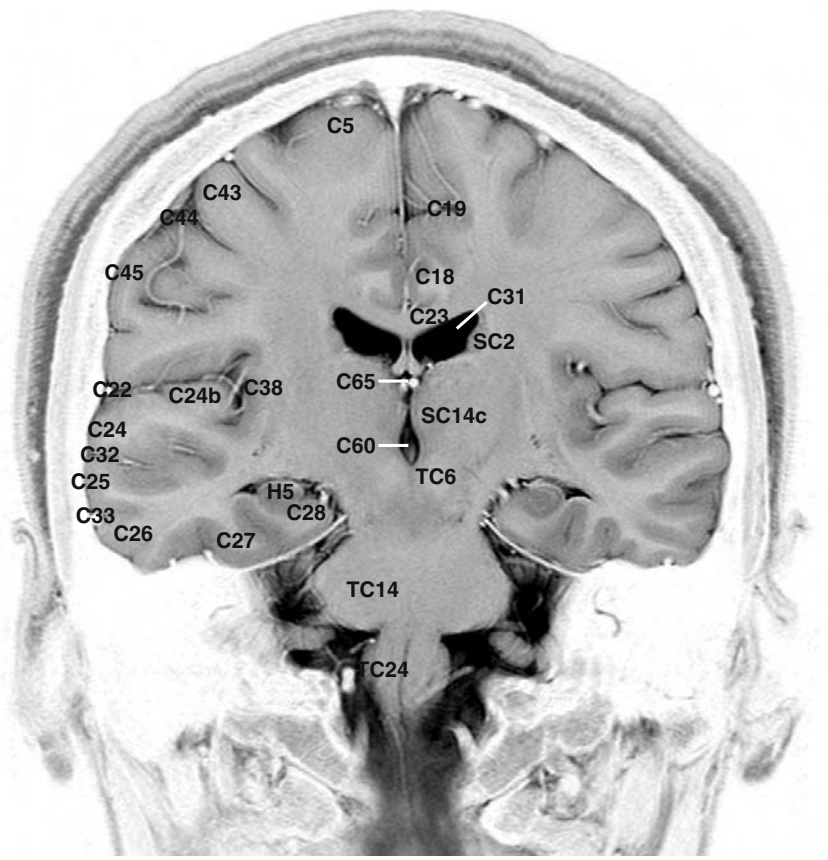


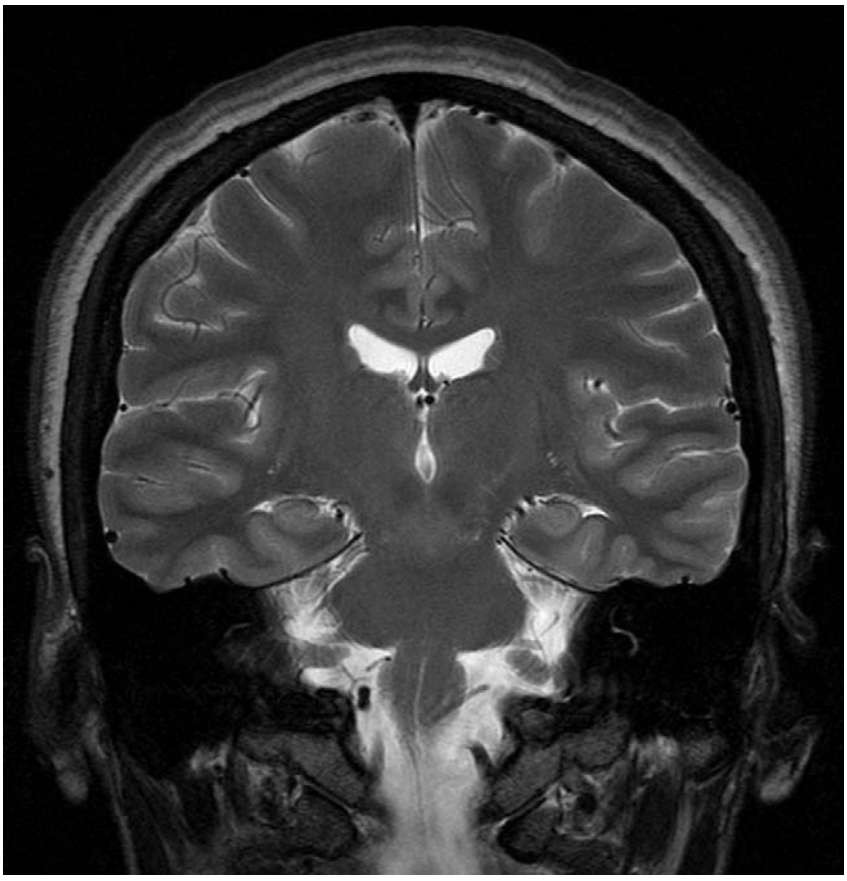

C4
C6
C5
C42a
C19
C43
C18
C23
C45
C44
C31a
C36
SC2
SC1
C43
SC5b
C39
C22
SC3
SC4a
C24a
SC4b
C58a
C24
C38
C32
H3
C61
C36
C31d
C25
H1
C34
C33
H4
C35
C26
C27

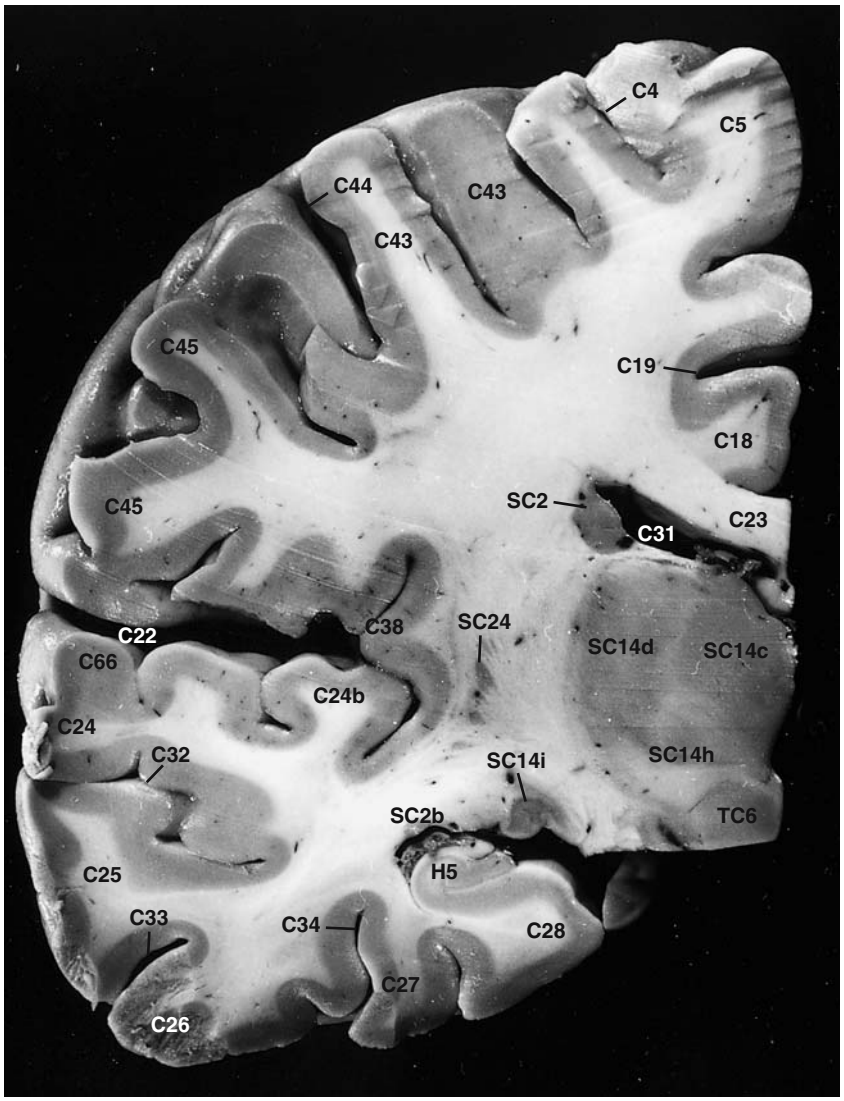

C5
C42a
C43
C19
C18
C44
C45
C23
C31a
SC2
C36
SC5
C22
C38
SC14a
SC3
C24
SC14c
SC4
C32
TC5
C25
H5a
C23
C26
C27
C28
TC14

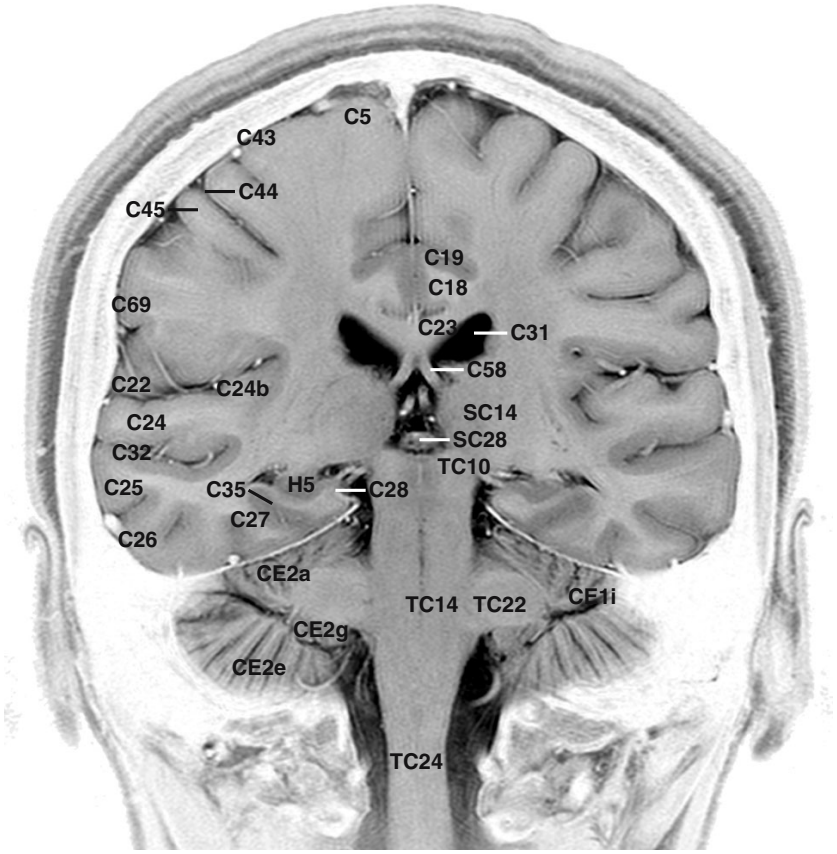


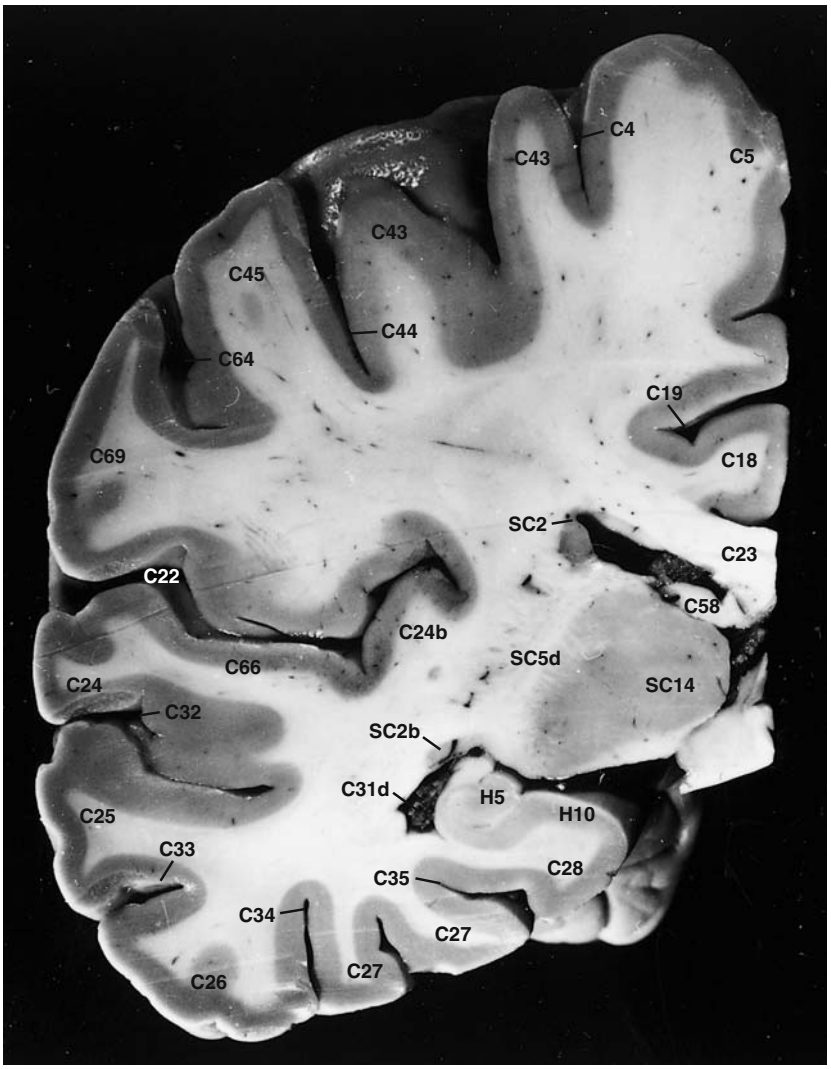

C5
C42a
C19
C43
C18
C44
C45
C23
SC2
C31a
C36
SC14a
SC14d
C51
SC5c
SC19
C22
SC3
SC14c
C24b
C38
SC4a
SC18
C24
TC5
C32
C63
H5a
C25
C34
SC31d
C28
C33
C27
C26

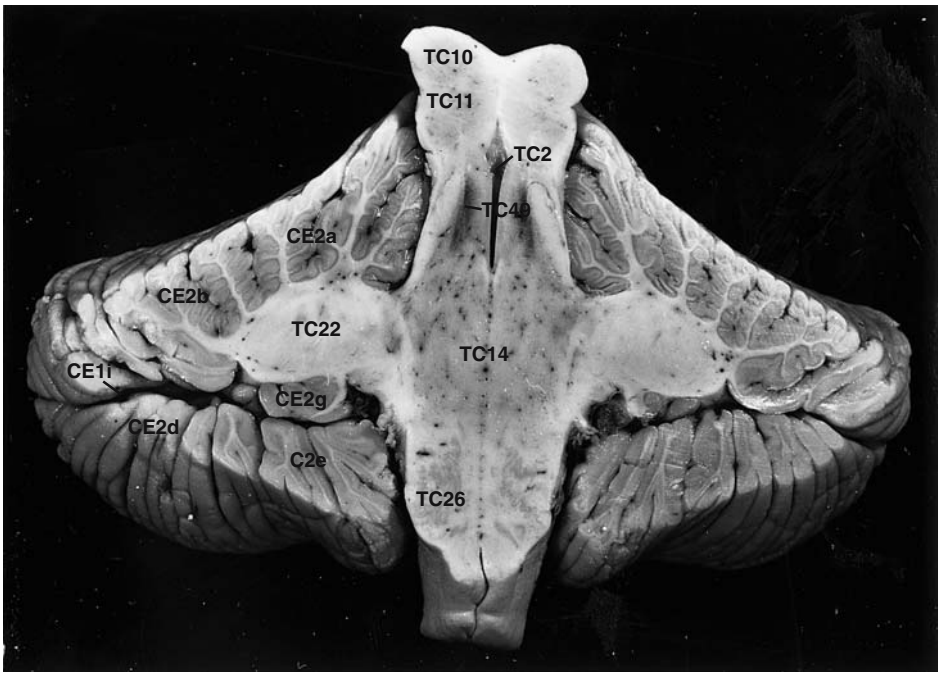

C5
C43
C44
C19
C45
C18
C31
C23
SC2
C22
C24b
C38
C65
SC14c
C24
C32
C60
TC6
C25
H5
C28
C33
C26
C27
TC14
TC24

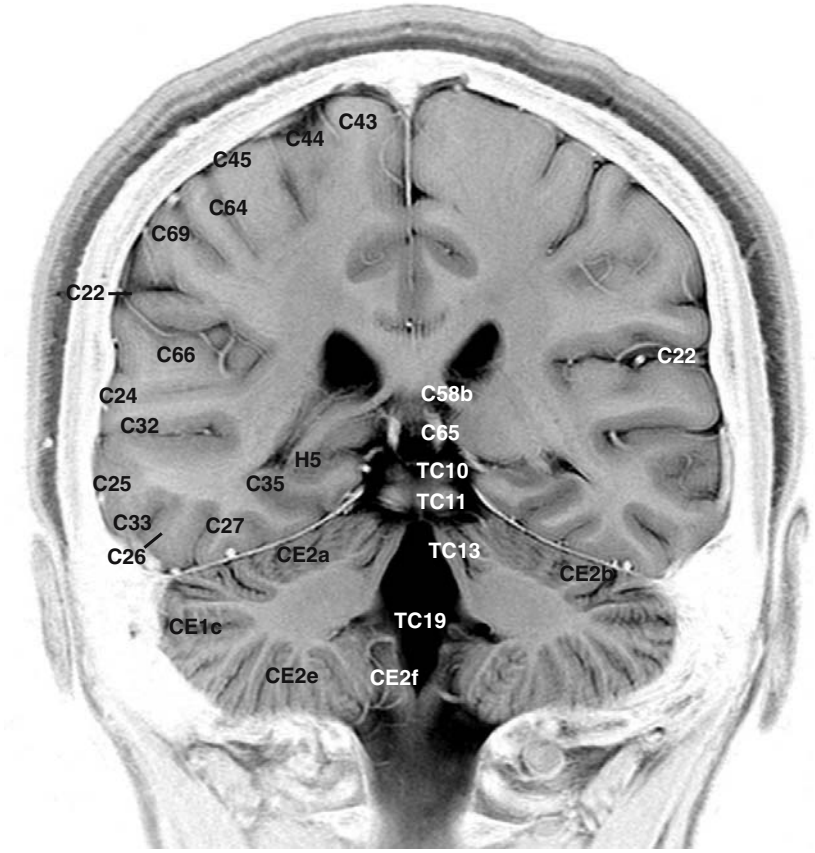


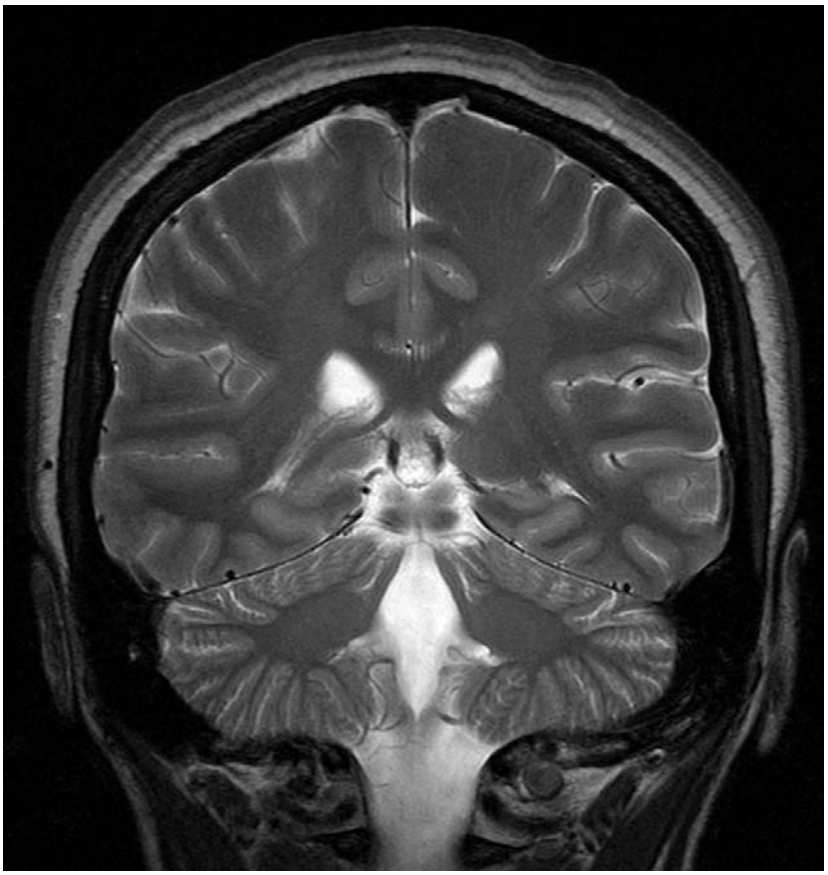

C4
C5
C44
C43
C43
C45
C19
C18
C45
SC2
C23
C31
C22
C38
SC24
SC14d
SC14c
C66
C24b
C24
C32
SC14i
SC14h
SC2b
TC6
C25
H5
C33
C34
C28
C27
C26

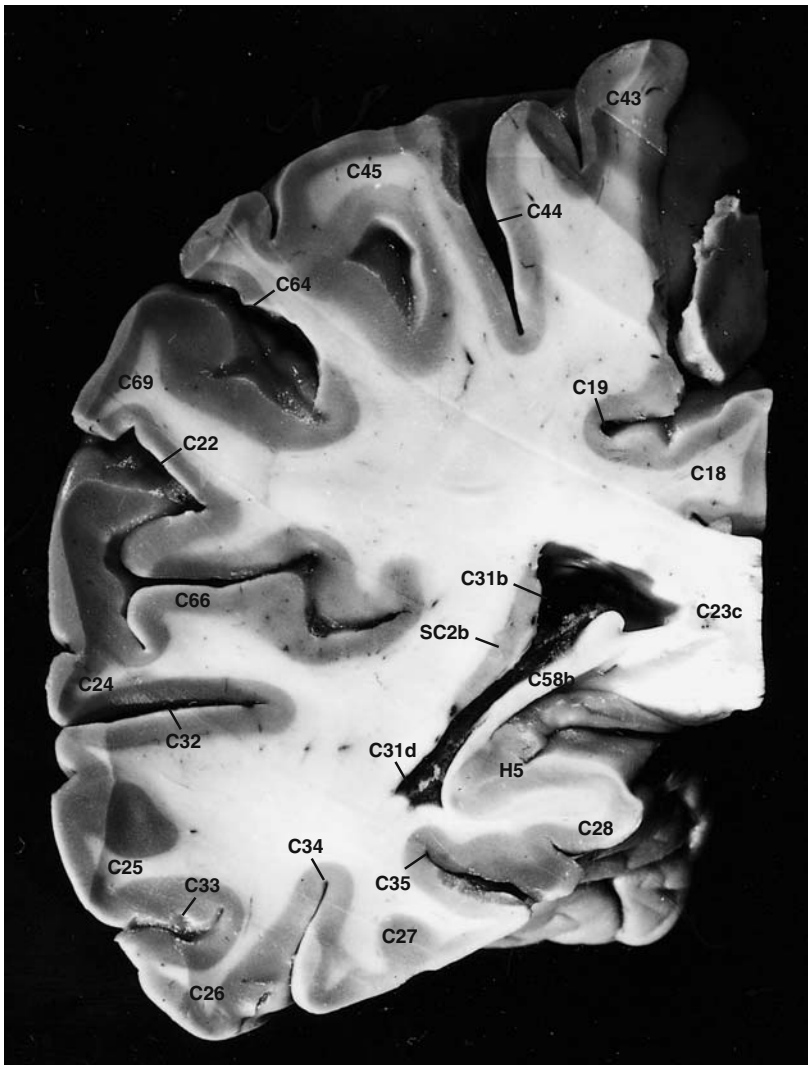

C5
C43
C44
C45
C19
C18
C69
C23
C31
C58
C22
C24b
SC14
C24
SC28
C32
TC10
C25
C35
H5
C28
C27
C26
CE2a
TC14
TC22
CE1i
CE2g
CE2e
TC24

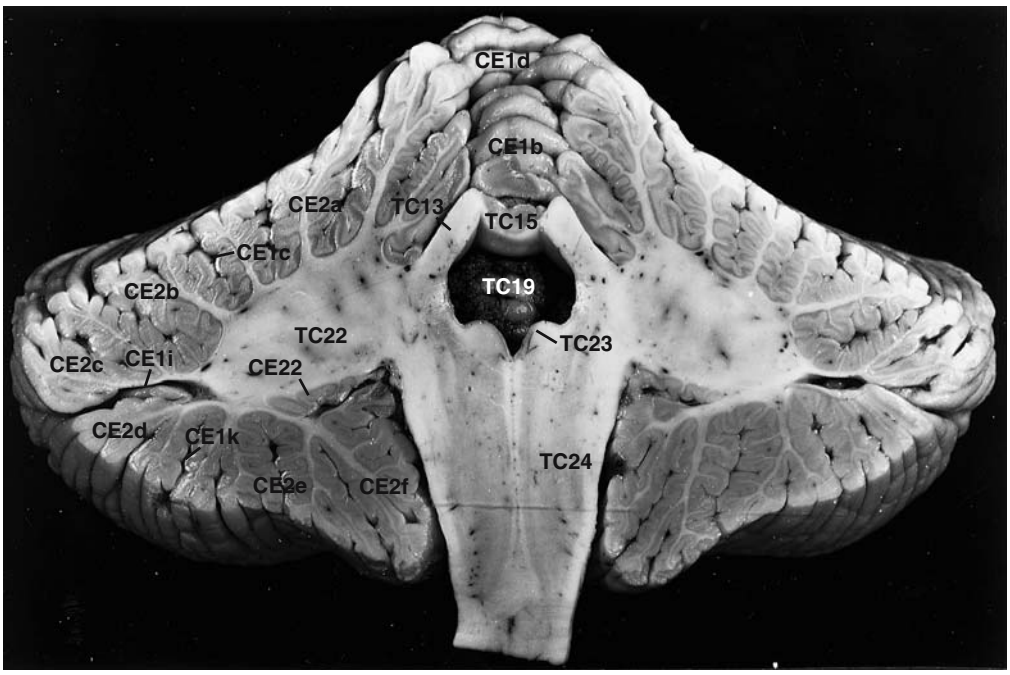

C4
C43
C5
C43
C45
C44
C64
C19
C69
C18
SC2
C23
C22
C58
C24b
SC5d
C66
C24
SC14
C32
SC2b
C31d
H5
H10
C25
C33
C28
C35
C34
C27
C27
C26

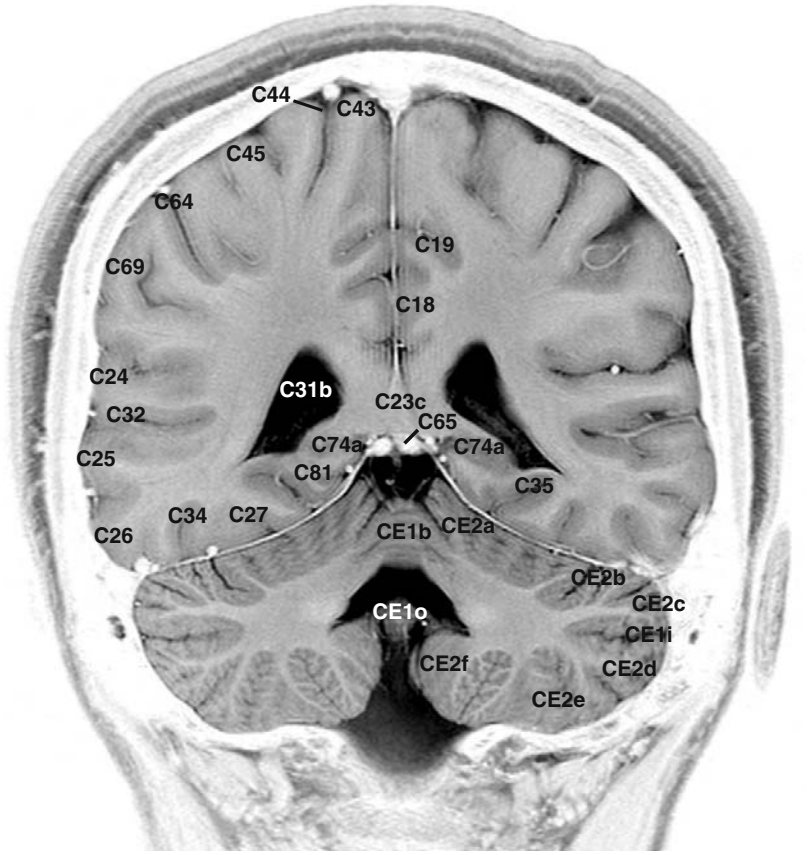

TC10
TC11
TC2
TC49
CE2a
CE2b
TC22
TC14
CE1i
CE2g
CE2d
C2e
TC26

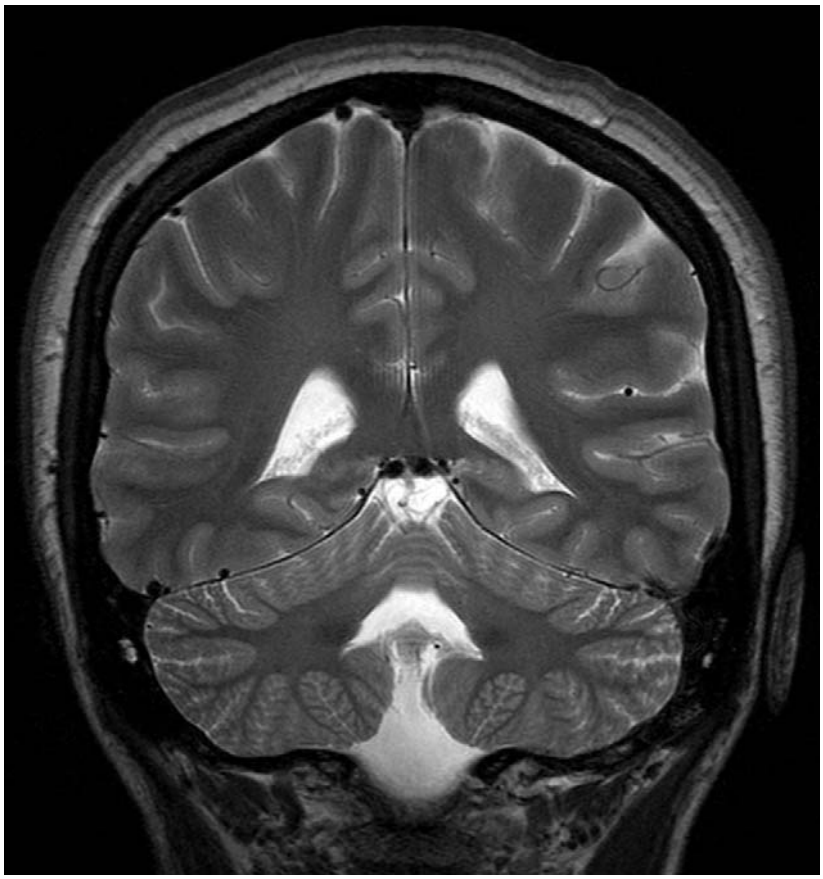

C43
C44
C45
C64
C69
C22
C66
C24
C32
C25
C35
H5
C33
C27
C26
CE2a
CE1c
CE2e
CE2f
C22
C58b
C65
TC10
TC11
TC13
CE2b
TC19

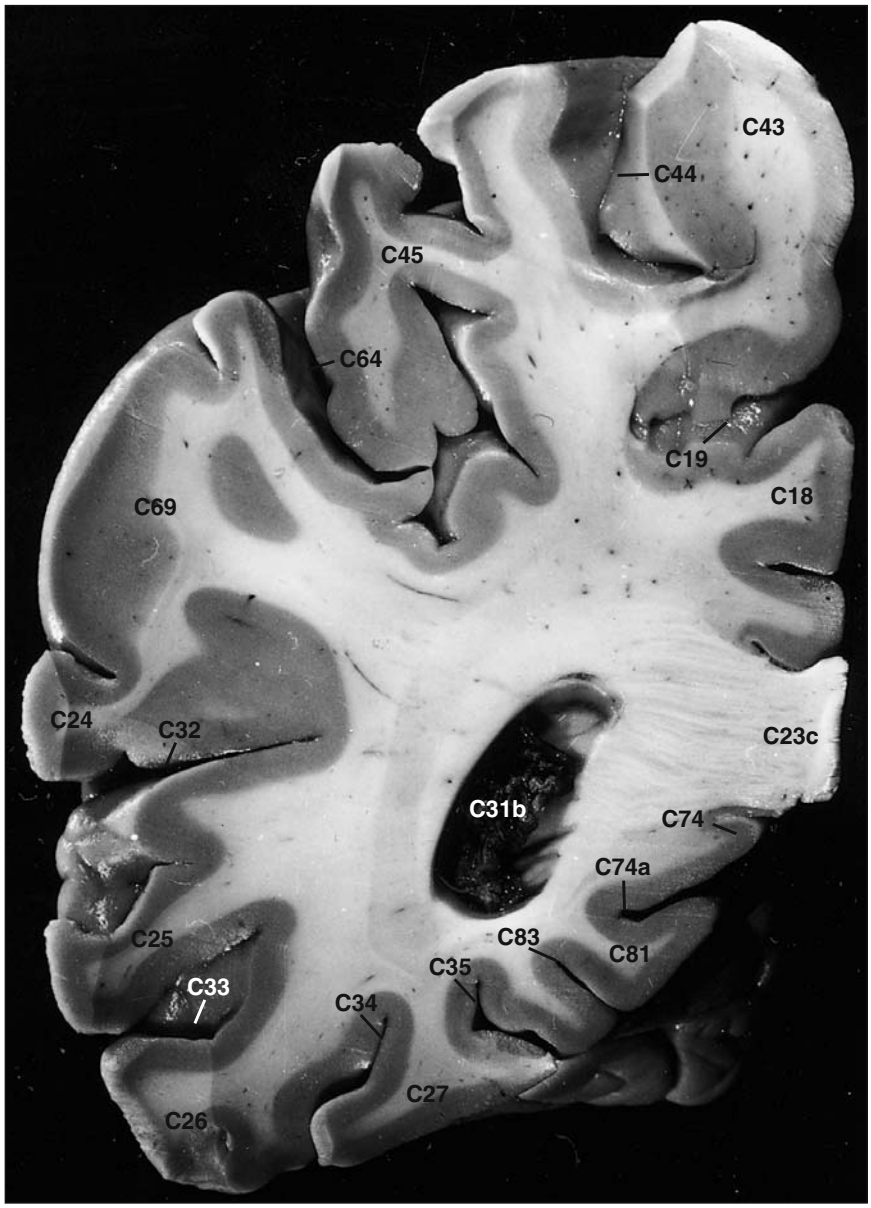


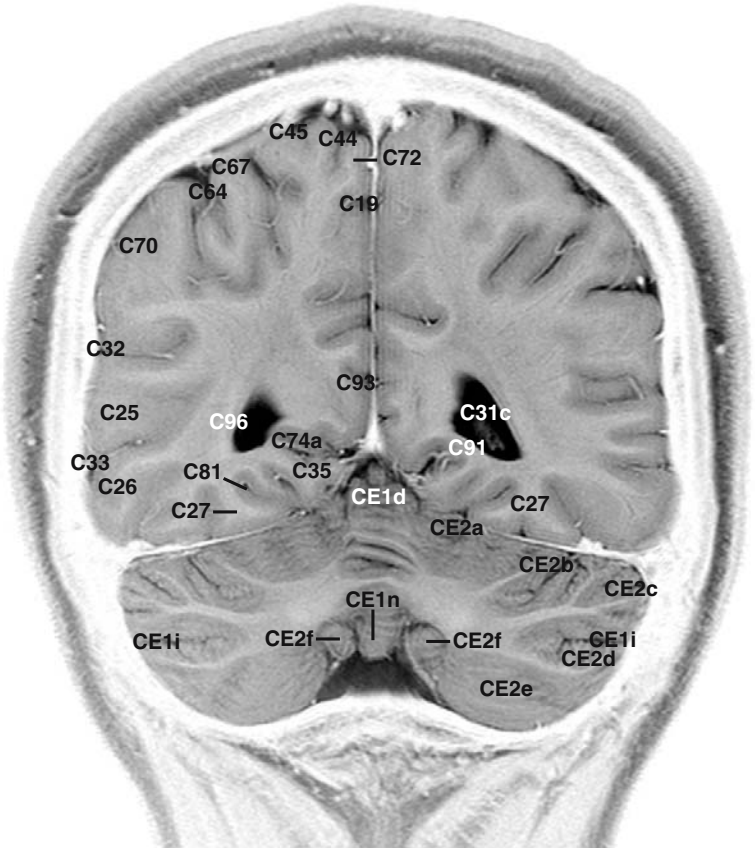

C43
C45
C44
C64
C69
C19
C22
C18
C31b
C66
C23c
SC2b
C24
C58b
C32
C31d
H5
C28
C34
C25
C33
C35
C27
C26

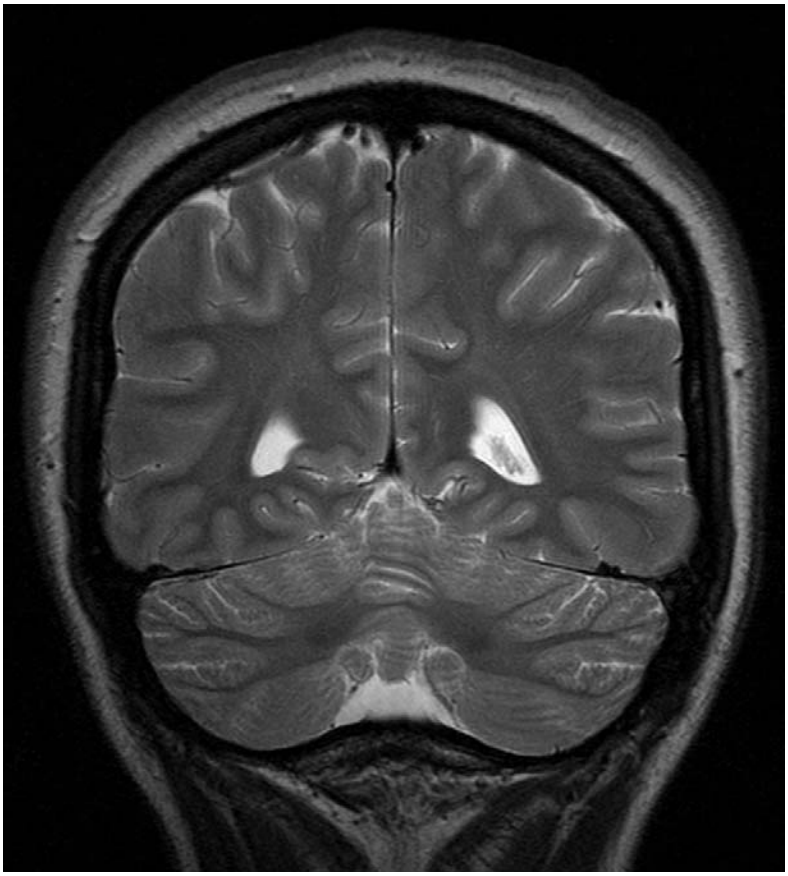

CE1d
CE1b
CE2a
TC13
TC15
CE1c
TC19
CE2b
TC22
TC23
CE2c
CE1i
CE22
CE2d
CE1k
TC24
CE2e
CE2f

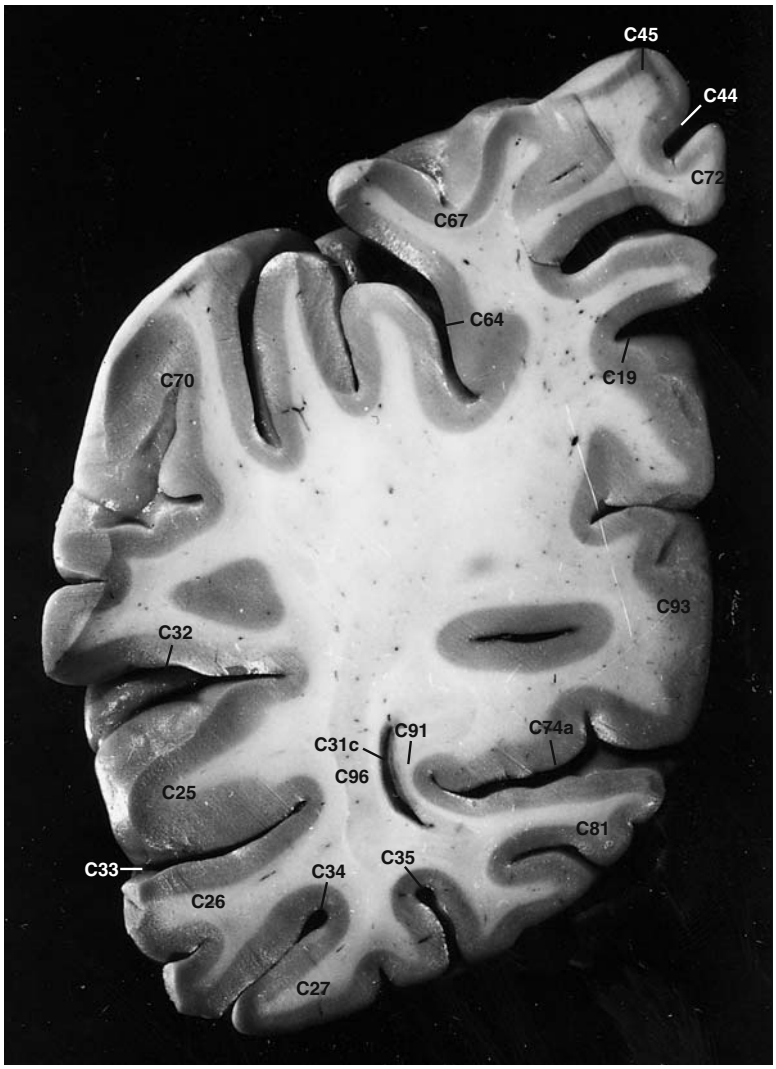

C44
C43
C45
C64
C19
C69
C18
C24
C31b
C23c
C32
C65
C74a
C74a
C25
C81
C35
C34
C27
CE1b
CE2a
C26
CE2b
CE2c
CE1o
CE1i
CE2f
CE2d
CE2e

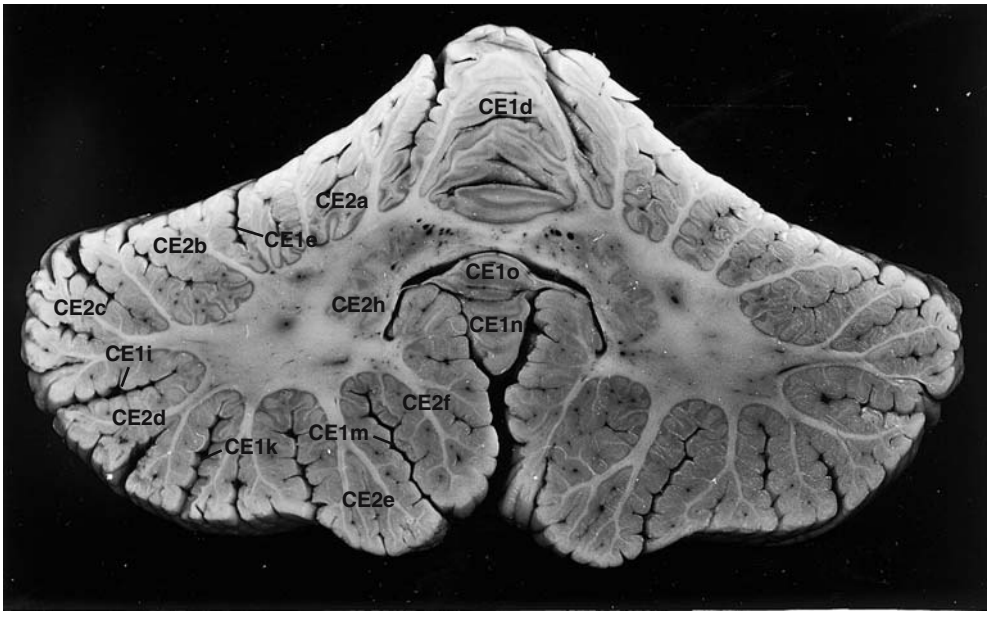


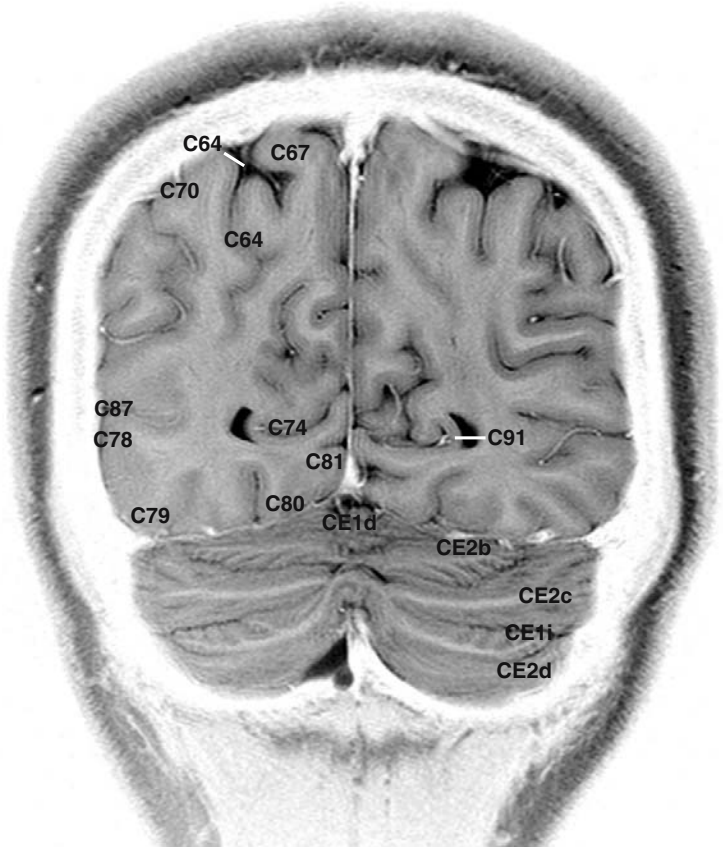

C43
C44
C45
C64
C19
C18
C69
C24
C32
C23c
C31b
C74
C74a
C25
C83
C81
C35
C33
C34
C27
C26

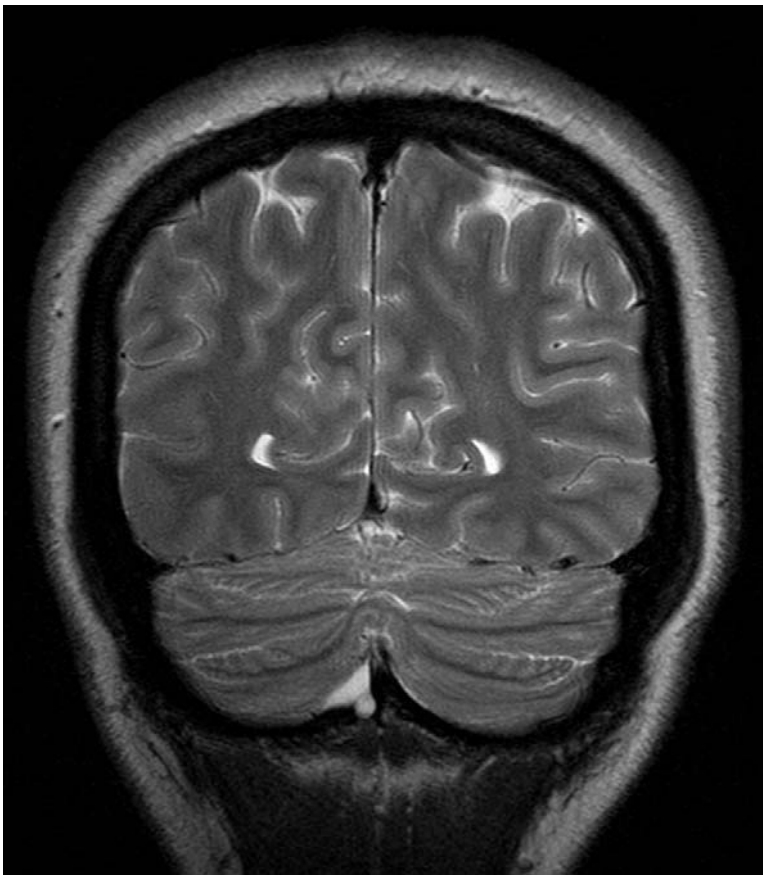

C45
C44
C72
C67
C64
C19
C70
C32
C93
C25
C96
C31c
C74a
C91
C33
C81
C35
C26
CE1d
C27
C27
CE2a
CE2b
CE2c
CE1n
CE1i
CE2f
CE2f
CE1i
CE2d
CE2e

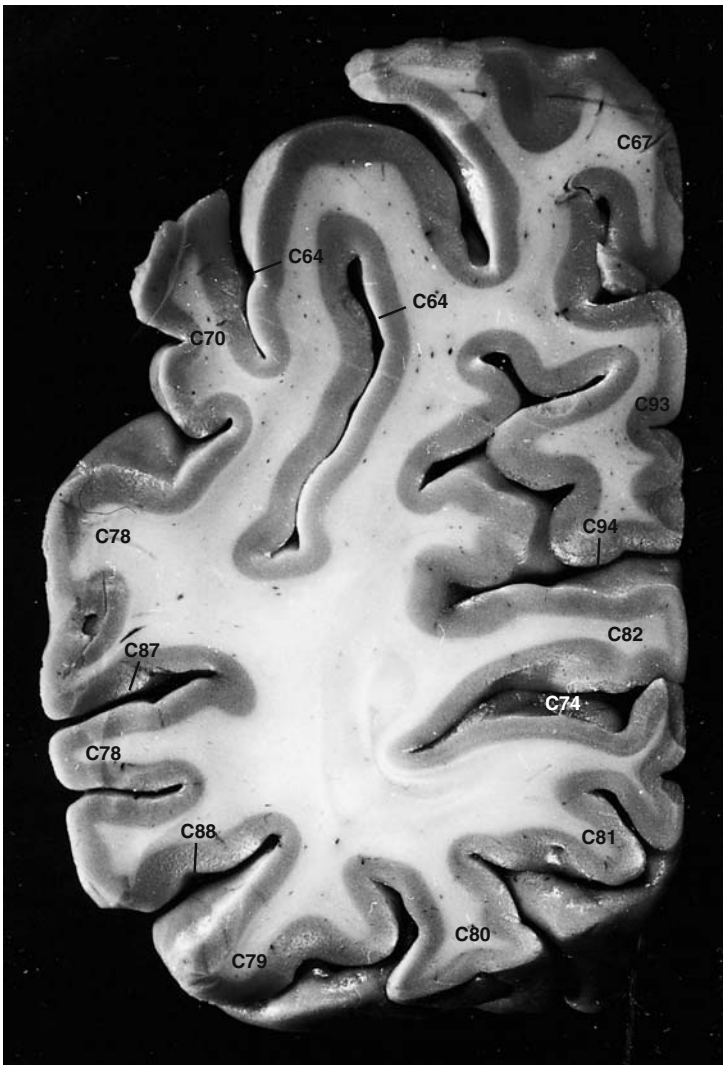


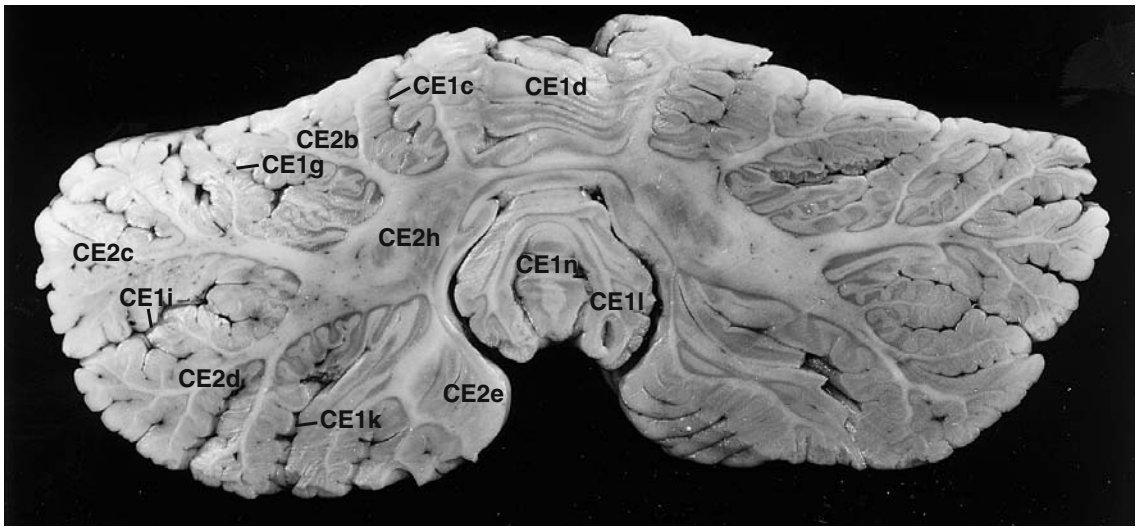

C45
C44
C72
C67
C64
C70
C19
C93
C32
C91
C74a
C31c
C96
C25
C81
C33
C34
C35
C26
C27


CE1d
CE2a
CE2b
CE1a
CE1o
CE2c
CE2h
CE1n
CE1i
CE2f
CE2d
CE1m
CE1k
CE2e


C64
C67
C70
C64
C87
C78
C74
C91
C81
C79
C80
CE1d
CE2b
CE2c
CE1i
CE2d

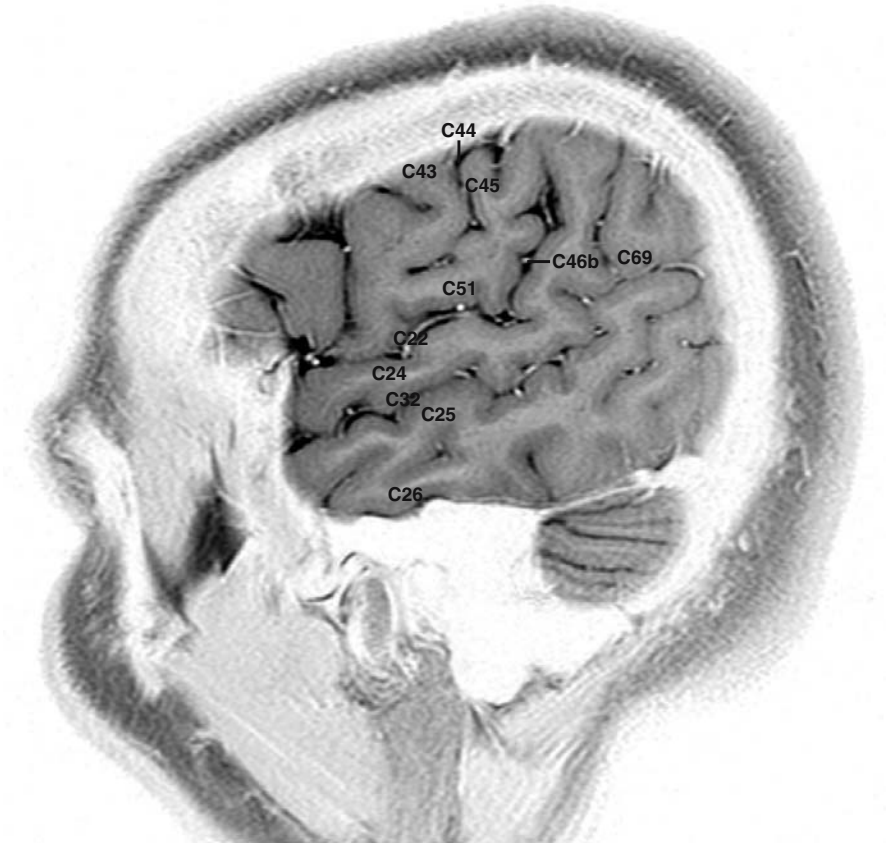


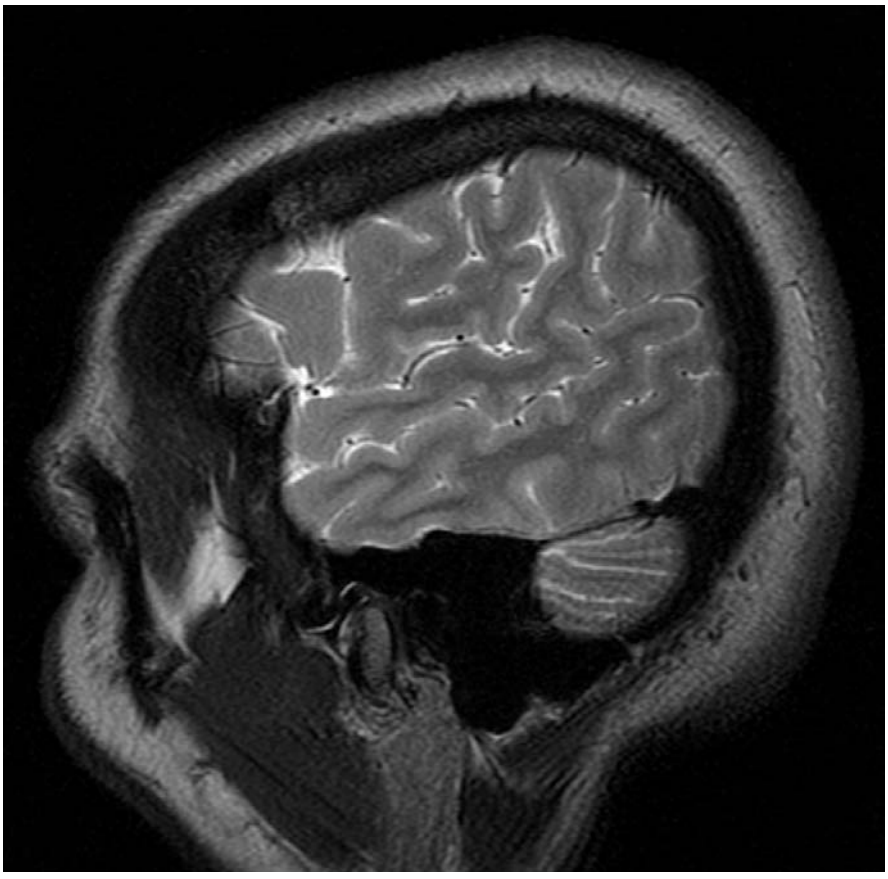

C67
C64
C64
C70
C93
C78
C94
C82
C87
C74
C78
C88
C81
C80
C79

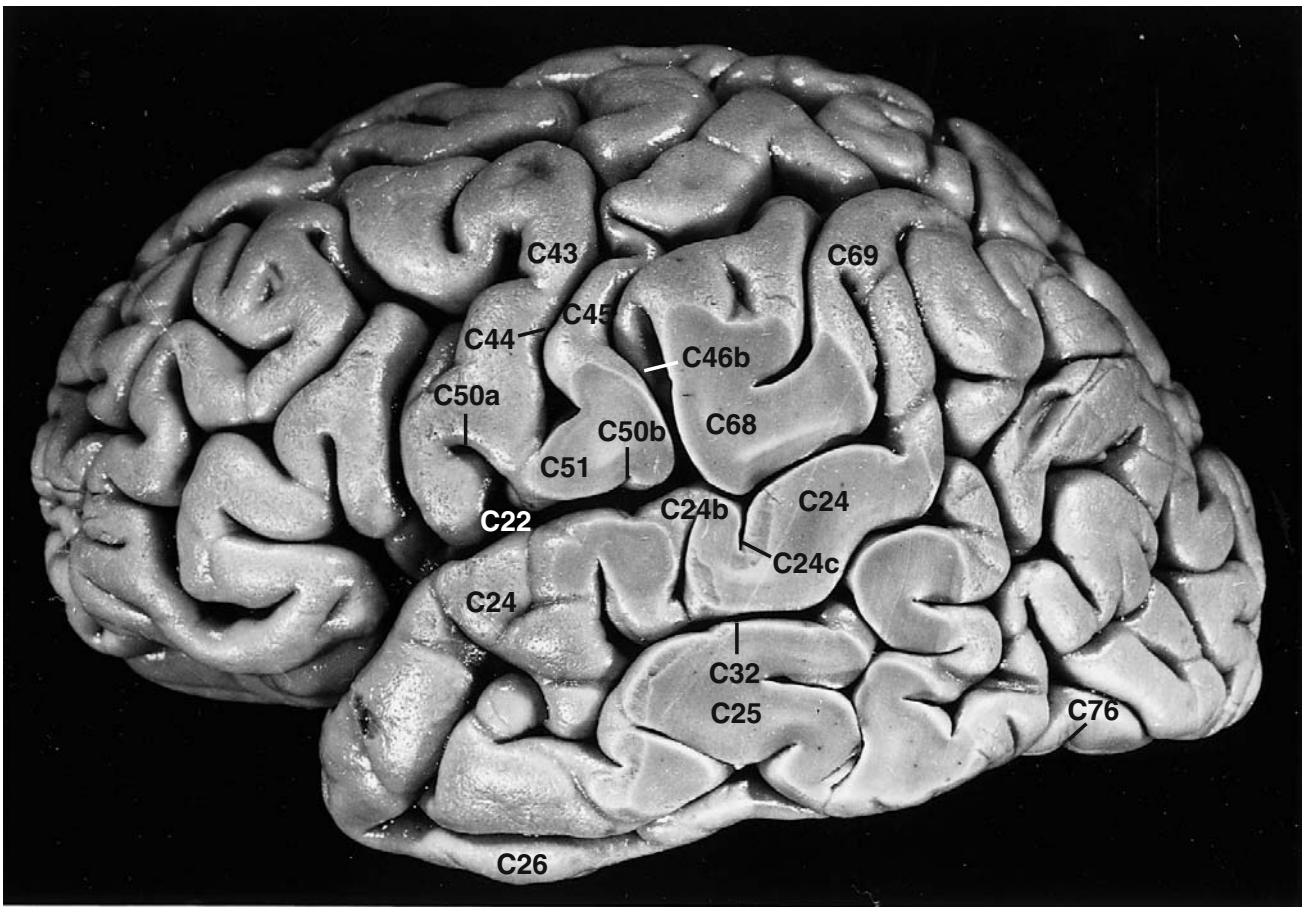

CE1c
CE1d
CE2b
CE1g
CE2h
CE2c
CE1n
CE1i
CE1l
CE2d
CE2e
CE1k

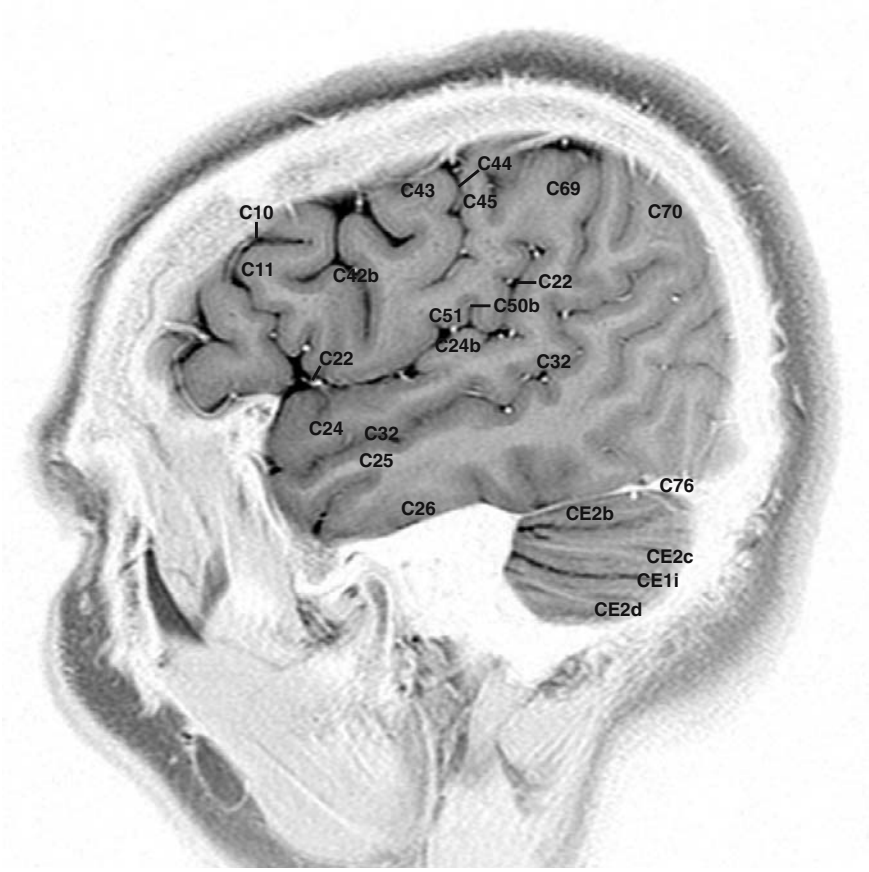
SAGITTAL CUTS

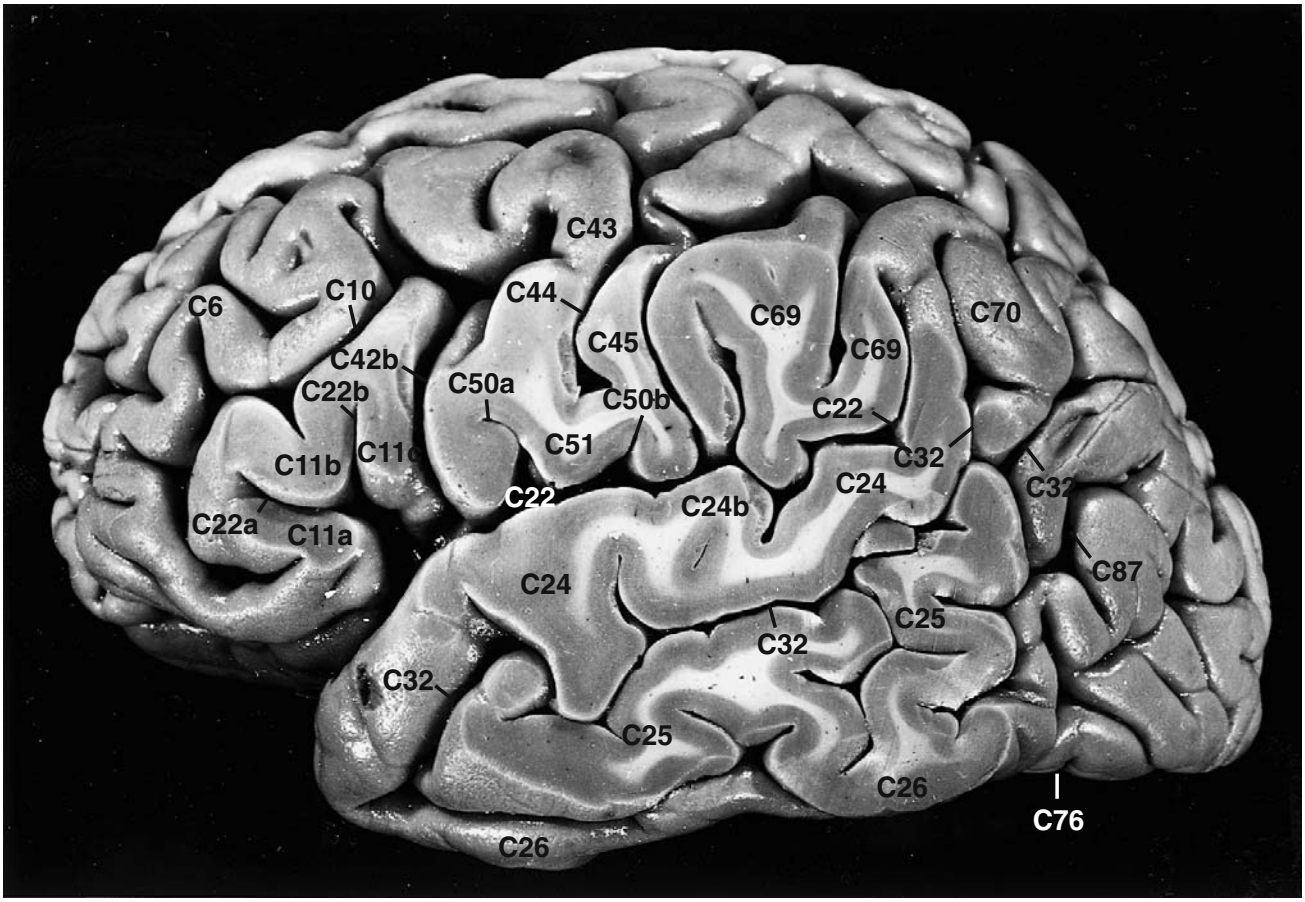
In the following pages (86 – 105), high definition T2-W FSE sagittal MR cuts (left) are compared with “traditional” anatomical cuts (right).
See the jacket flap for anatomical references.


C44
C43
C45
C46b
C69
C51
C22
C24
C32
C25
C26

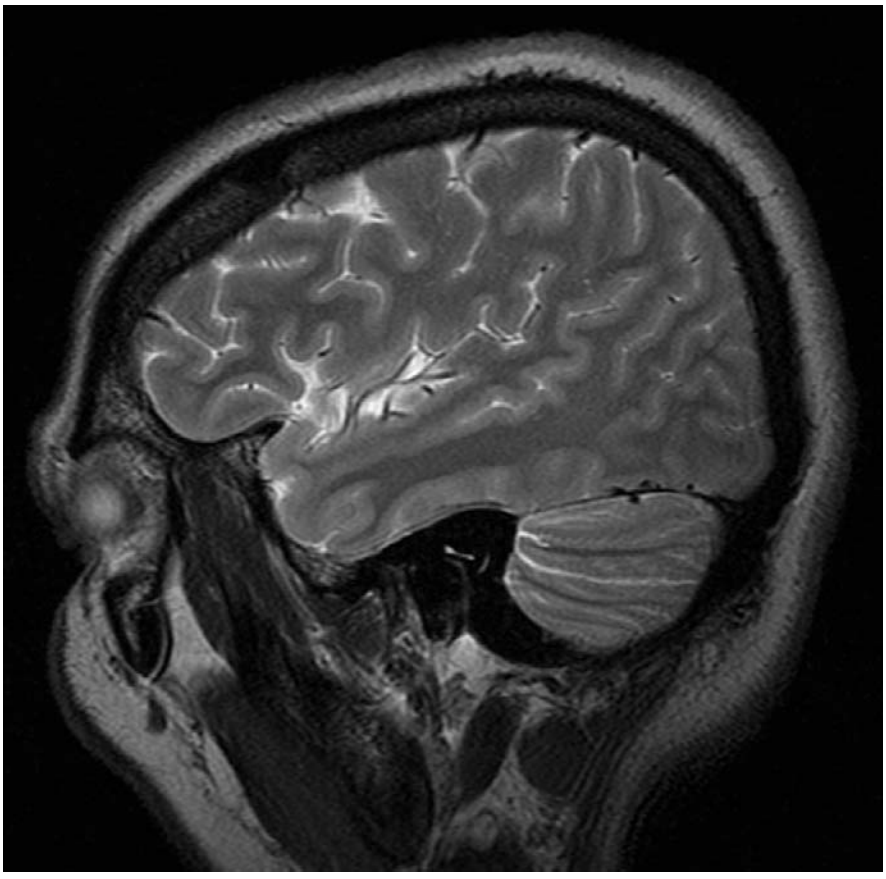


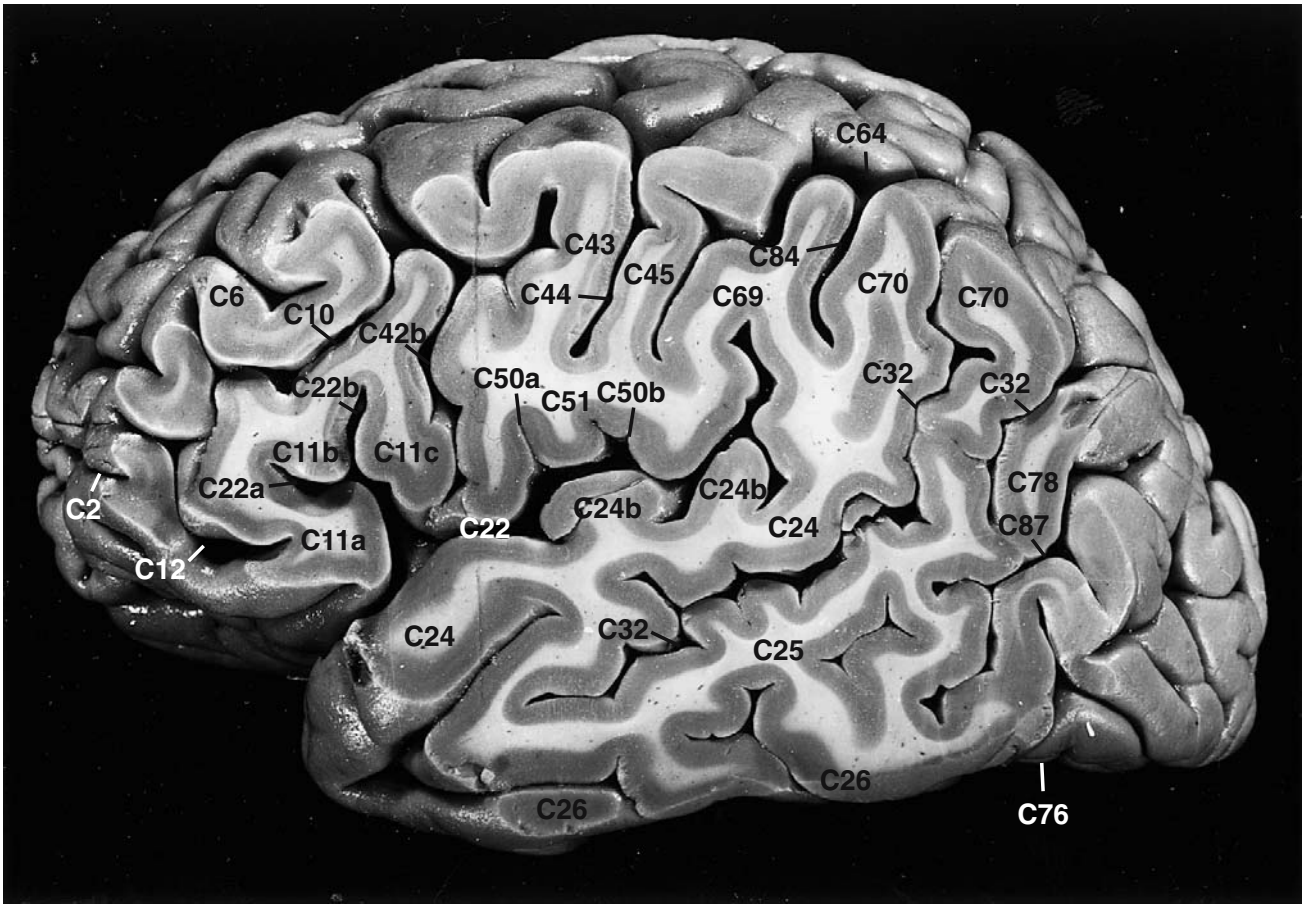

C43
C69
C45
C44
C46b
C50a
C68
C50b
C51
C24
C24b
C22
C24c
C24
C32
C25
C76
C26

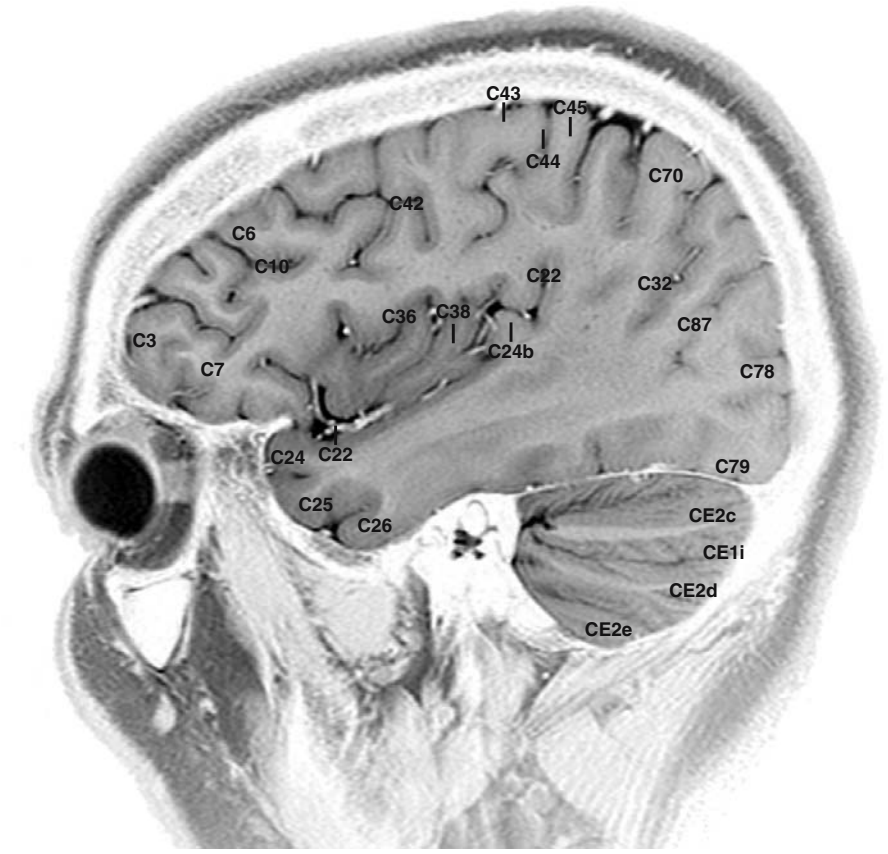

C44
C43
C45
C69
C70
C10
C11
C42b
C22
C51
C50b
C24b
C32
C22
C24
C32
C25
C76
C26
CE2b
CE2c
CE1i
CE2d

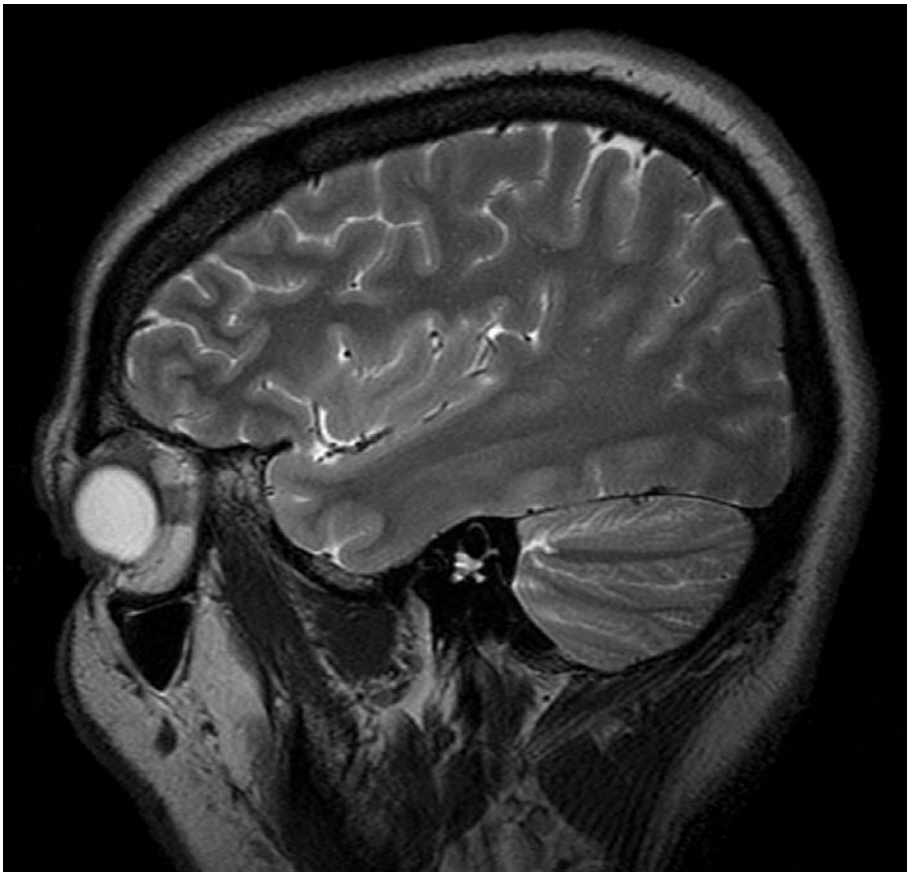

C43
C10
C6
C44
C69
C70
C45
C69
C42b
C50a
C22b
C50b
C22
C51
C32
C11b
C11c
C24
C32
C22
C24b
C22a
C11a
C87
C24
C25
C32
C32
C25
C26
C76
C26

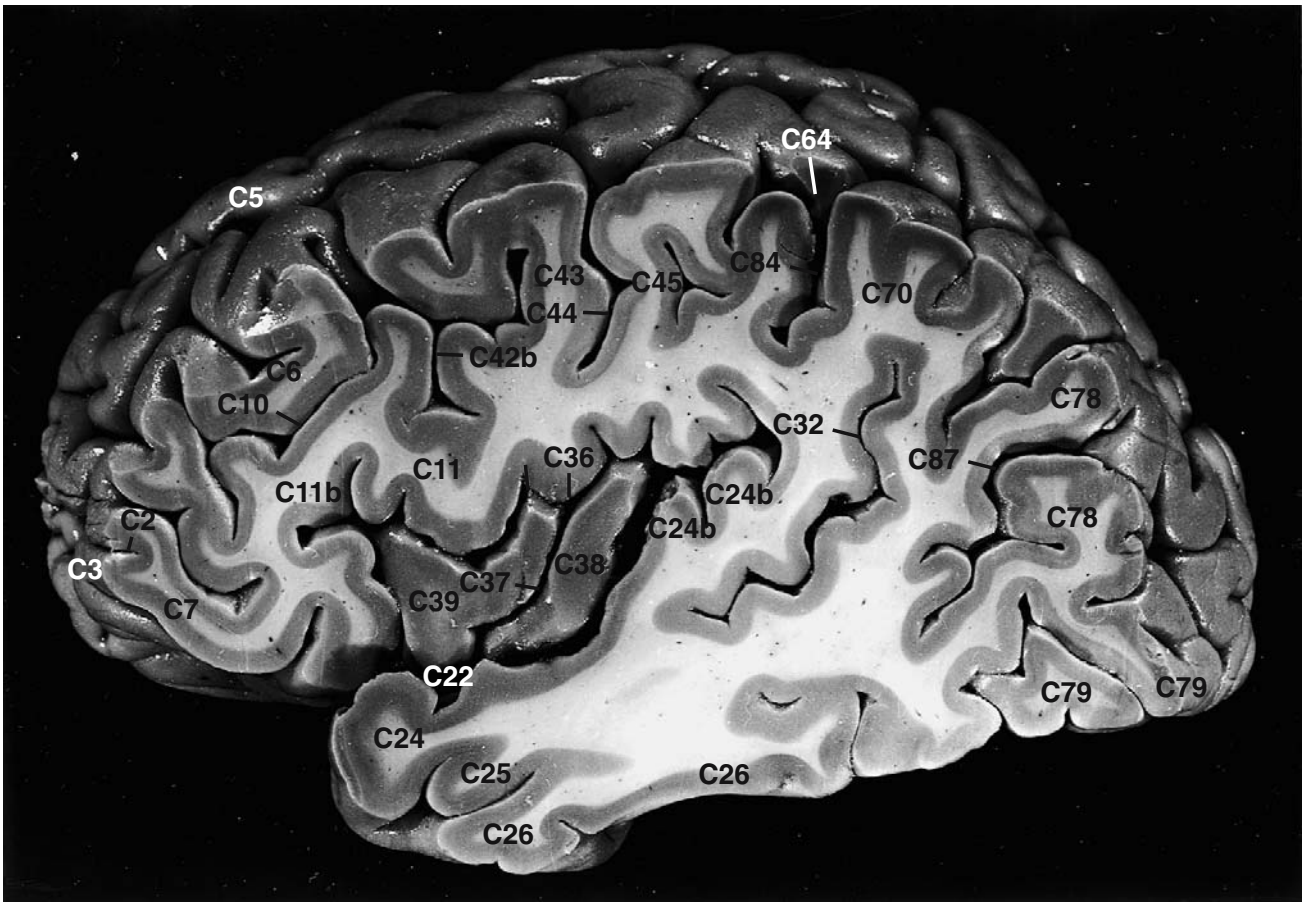
C43
C44
C45
C69
C70
C6
C10
C11
C50A
C50B
C32
C22B
C11C
C51
C24B
C87
C11B
C22A
C11A
C22
C32
C78
C24
C76
C79
C25
C26
CE2C
CE1I
CE2D

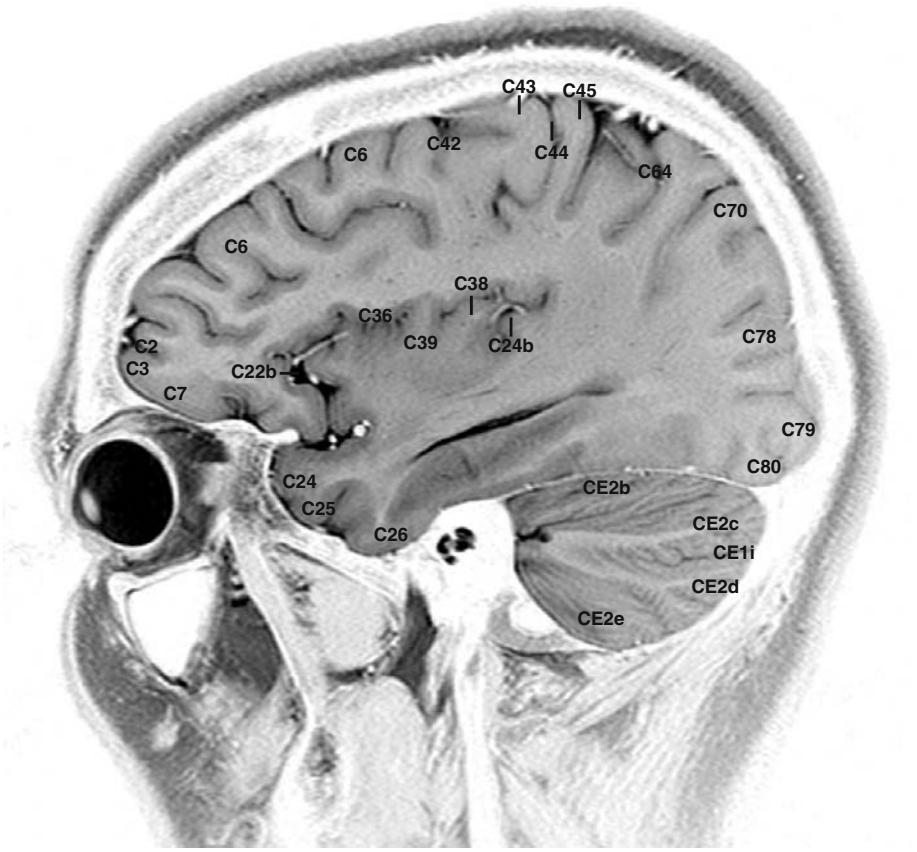


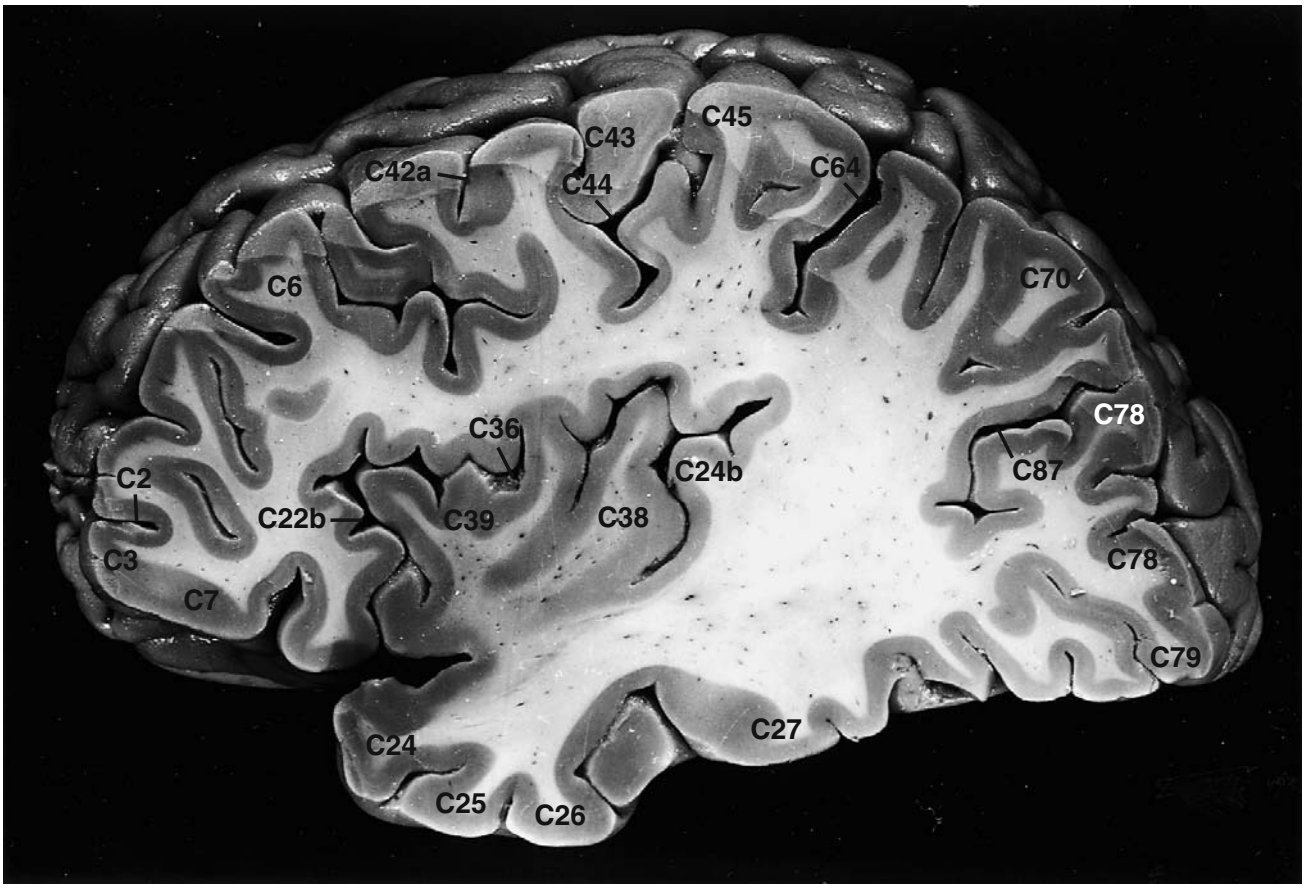

C64
C43
C84
C45
C44
C69
C70
C70
C6
C10
C42b
C50a
C51
C50b
C32
C32
C22b
C11b
C11c
C22a
C2
C24b
C24b
C78
C22
C24
C87
C11a
C12
C24
C32
C25
C26
C26
C76

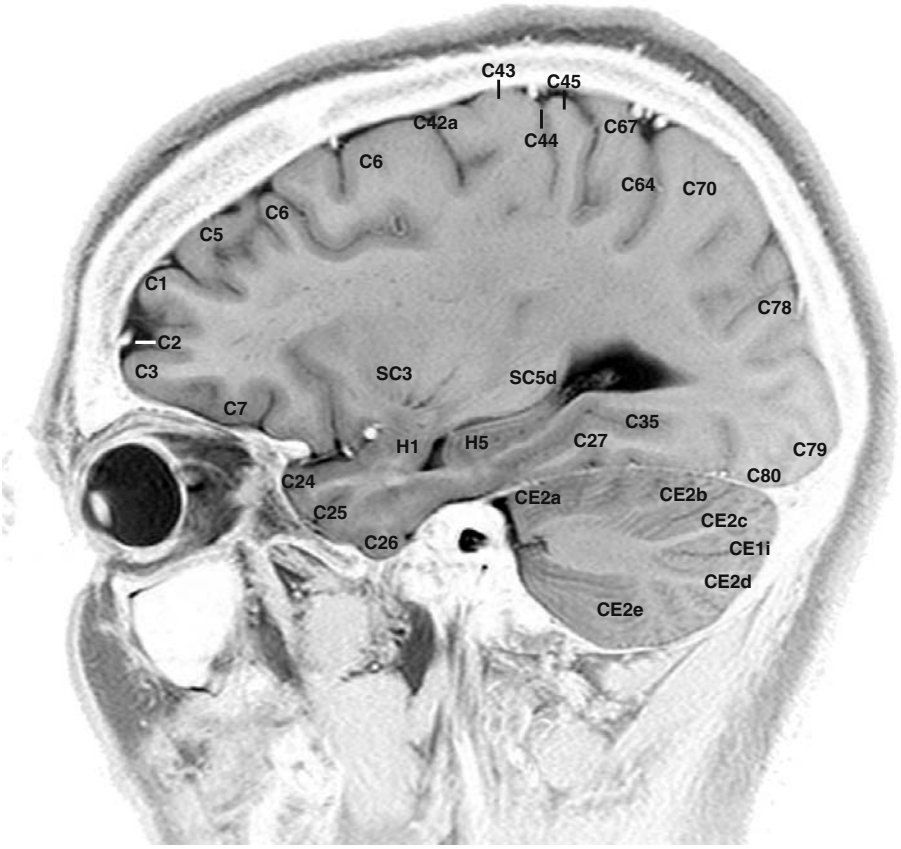

C43
C45
C44
C70
C42
C6
C10
C22
C32
C36
C38
C87
C3
C24b
C7
C78
C24
C22
C79
C25
CE2c
C26
CE1i
CE2d
CE2e

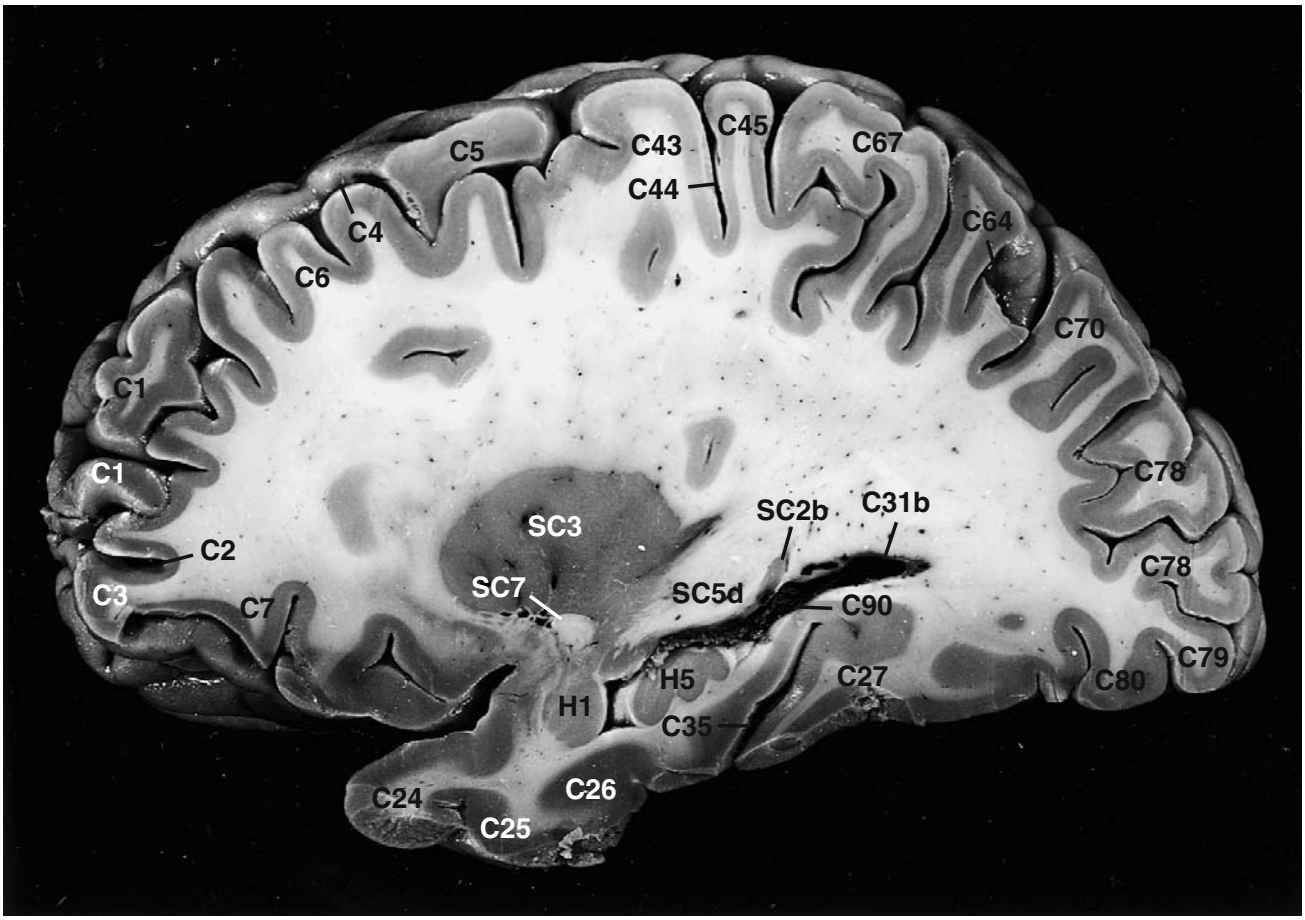


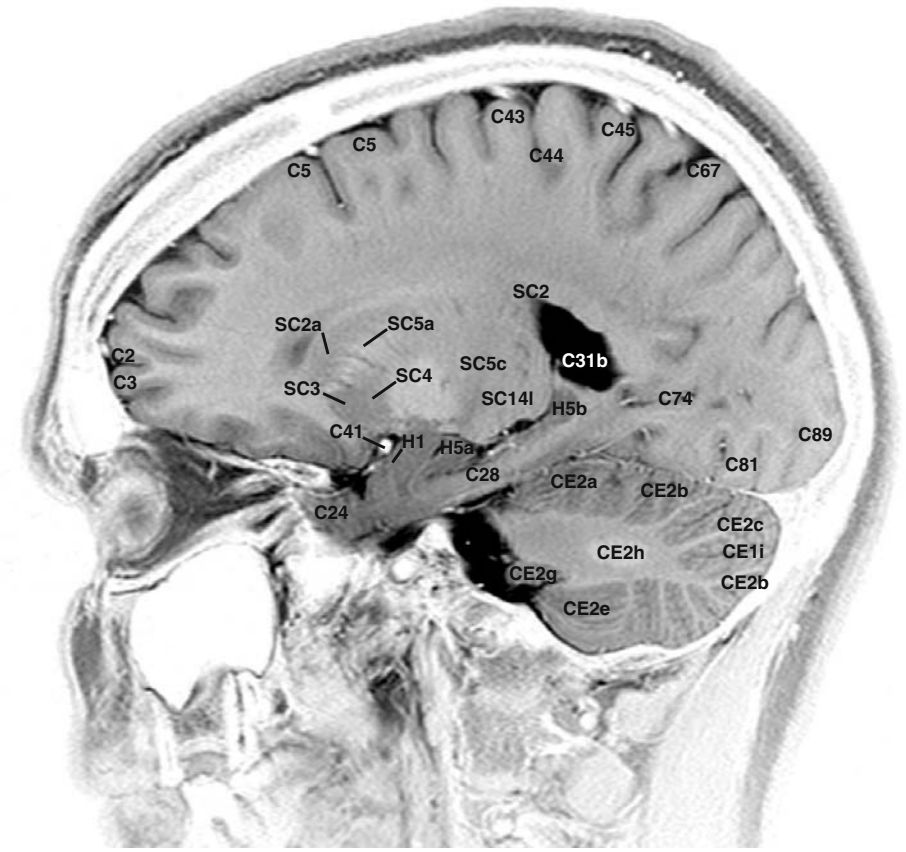

C64
C5
C84
C43
C45
C70
C44
C42b
C6
C10
C78
C32
C36
C87
C11
C11b
C24b
C2
C24b
C78
C3
C38
C37
C7
C39
C22
C79
C79
C24
C25
C26
C26

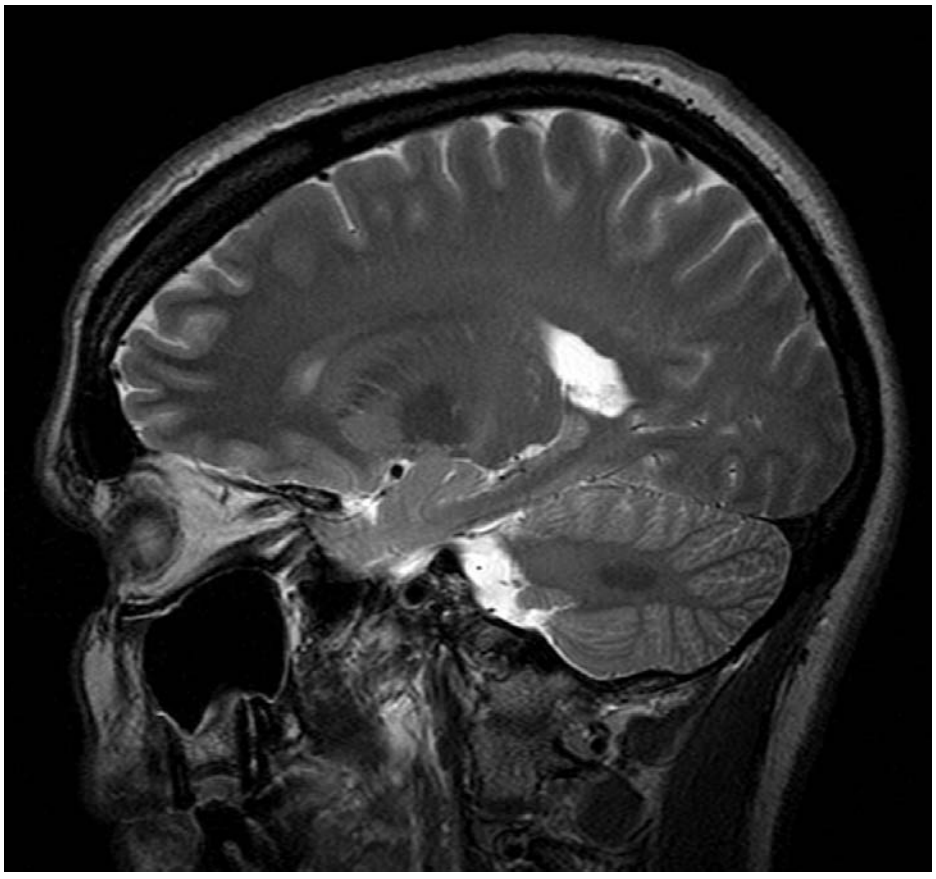

C43
C45
C42
C6
C44
C64
C70
C6
C38
C36
C39
C24b
C78
C2
C3
C22b
C7
C79
C80
C24
CE2b
C25
CE2c
C26
CE1i
CE2d
CE2e

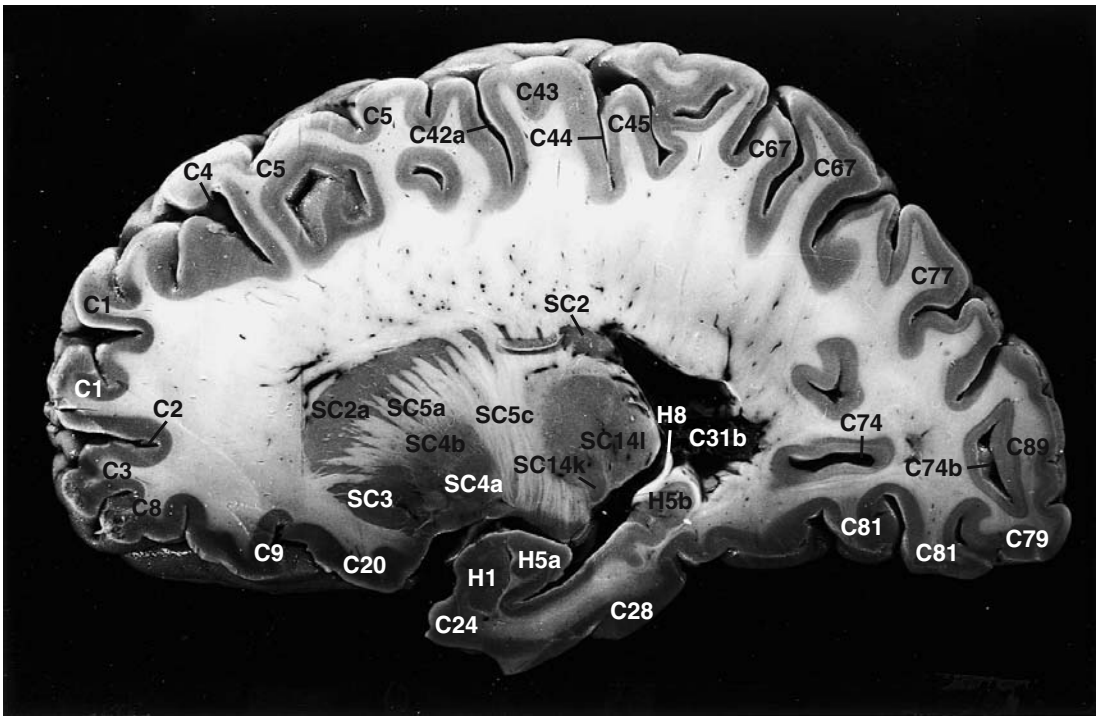

C43
C45
C42a
C44
C64
C6
C70
C78
C36
C24b
C87
C2
C22b
C39
C38
C3
C78
C7
C79
C27
C24
C25
C26

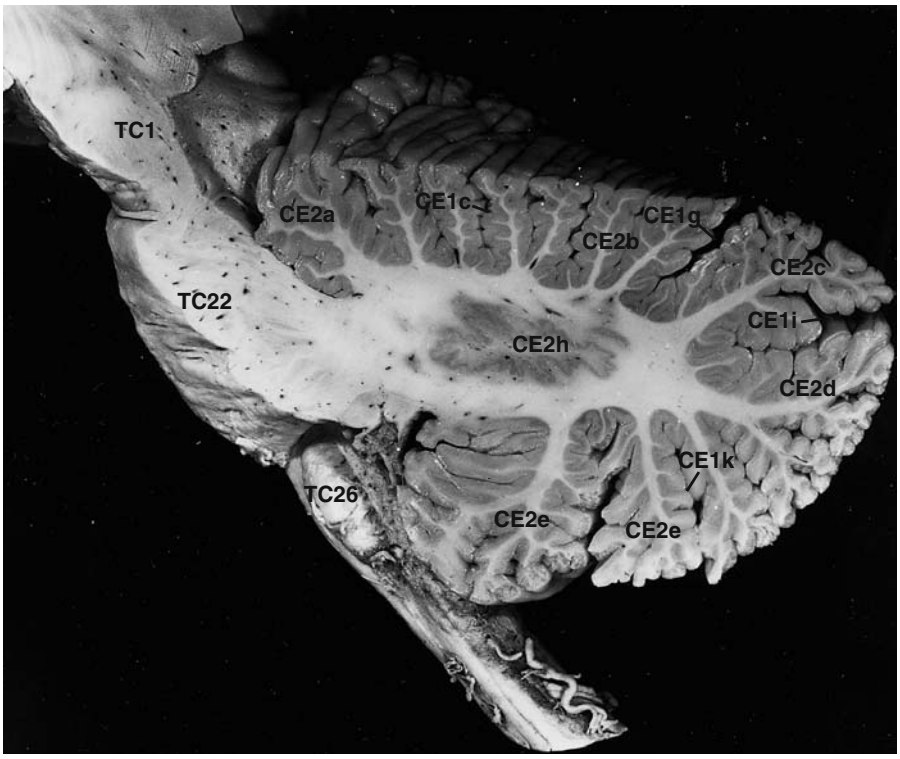

C43
C45
C42a
C44
C67
C6
C64
C70
C6
C5
C1
C78
C2
C3
SC3
SC5d
C7
C35
H1
H5
C27
C79
C24
C80
CE2a
CE2b
C25
CE2c
C26
CE1i
CE2d
CE2e

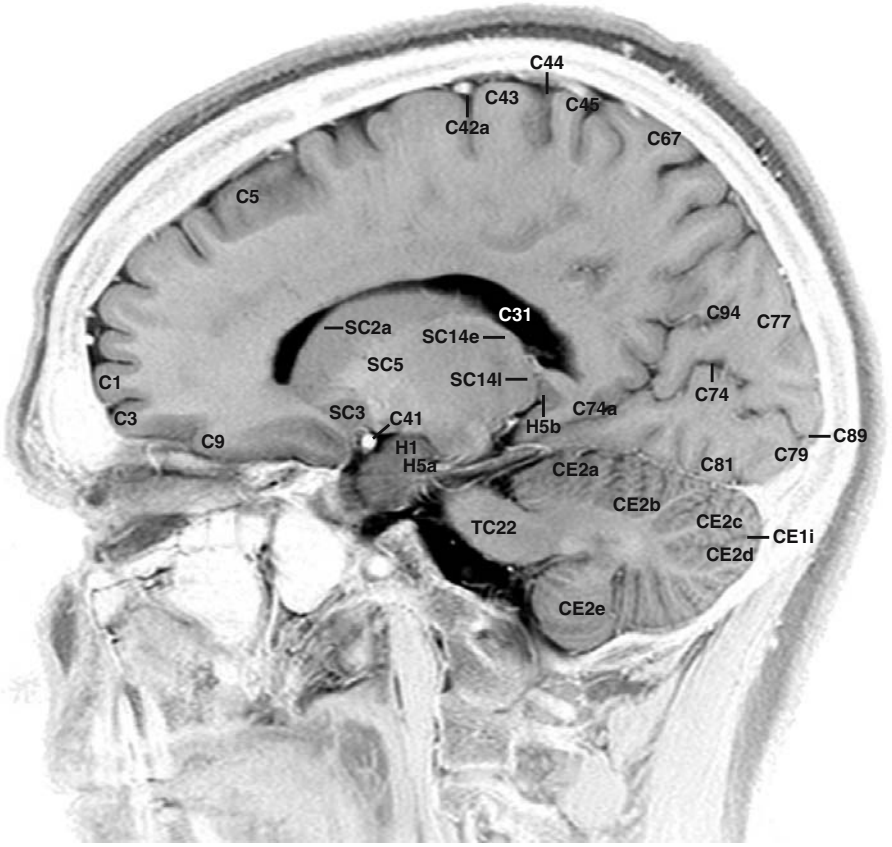

C5
C43
C45
C67
C44
C4
C64
C6
C70
C1
C1
C78
SC3
SC2b
C31b
C2
C78
SC7
SC5d
C90
C3
C7
C79
H5
C27
C80
H1
C35
C24
C26
C25

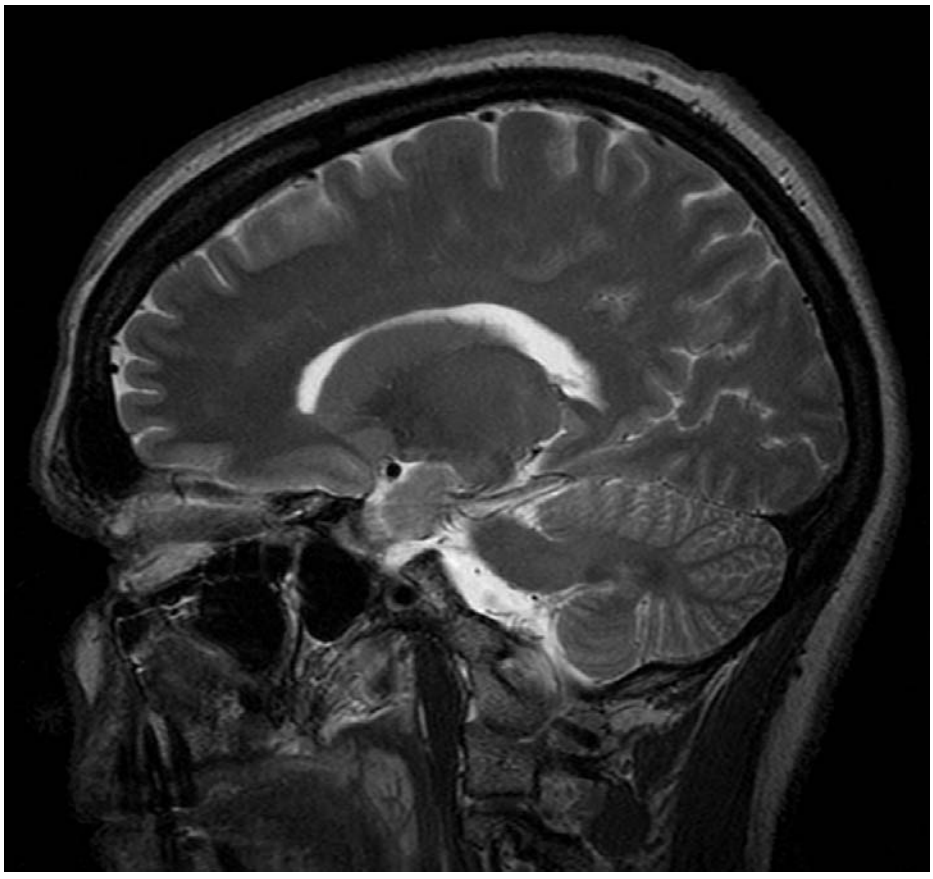

C43
C45
C5
C44
C5
C67
SC2
SC2a
SC5a
C2
C3
SC5c
C31b
SC3
SC4
SC14l
H5b
C74
C41
H1
H5a
C89
C28
C81
CE2a
CE2b
C24
CE2c
CE2h
CE1i
CE2g
CE2b
CE2e

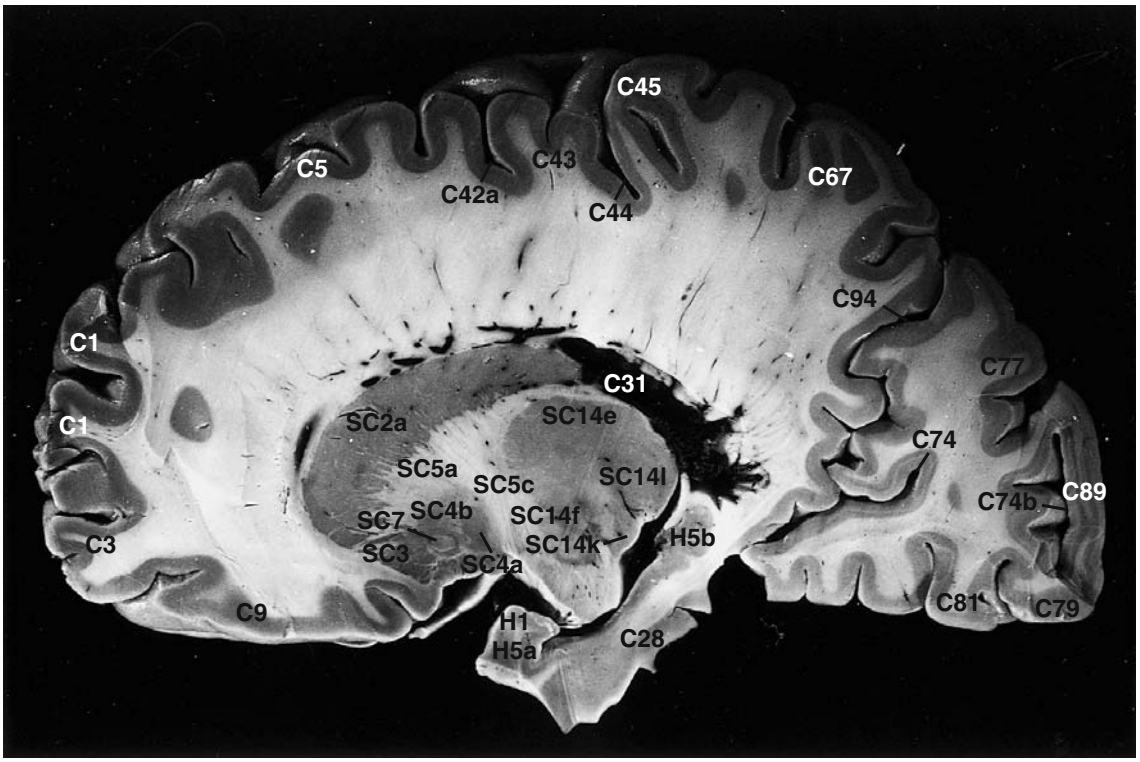



C43
C5
C42a
C44
C45
C67
C67
C4
C5
C77
C1
SC2
C1
C2
SC2a
SC5a
SC5c
H8
C74
C89
SC4b
SC14l
C31b
C74b
C3
SC14k
SC4a
SC3
H5b
C8
C81
C79
C9
C20
H5a
C81
H1
C28
C24

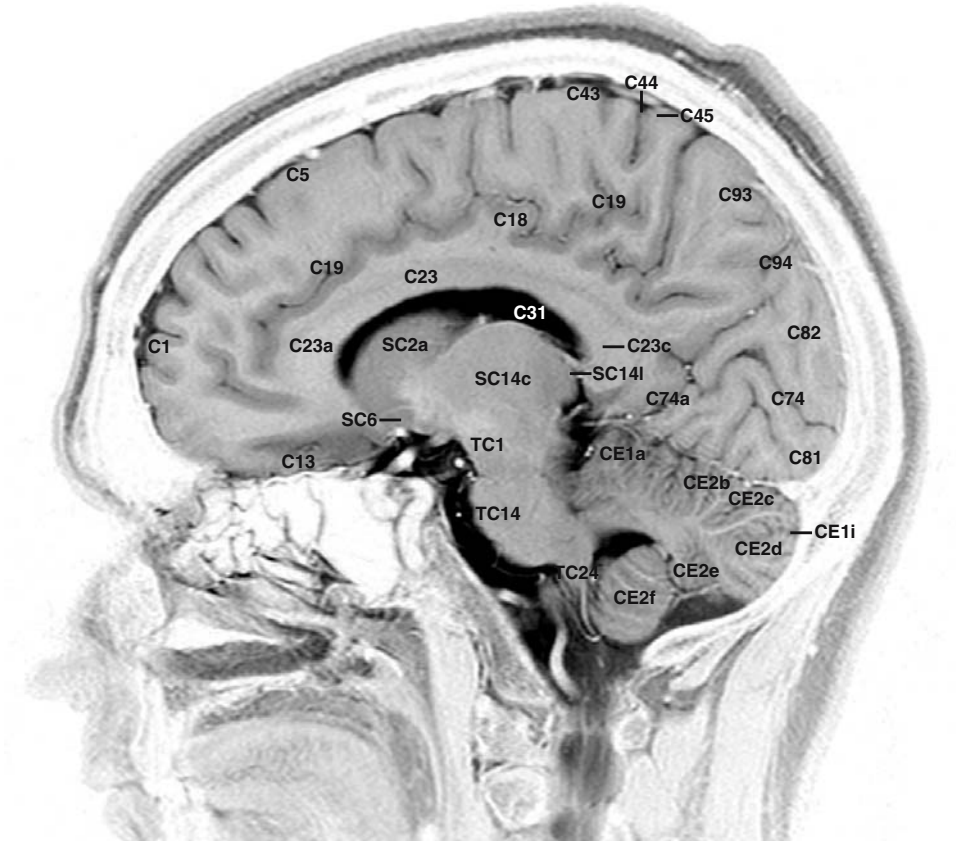

TC1
CE2a
CE1c
CE1g
CE2b
CE2c
TC22
CE1i
CE2h
CE2d
CE1k
TC26
CE2e
CE2e

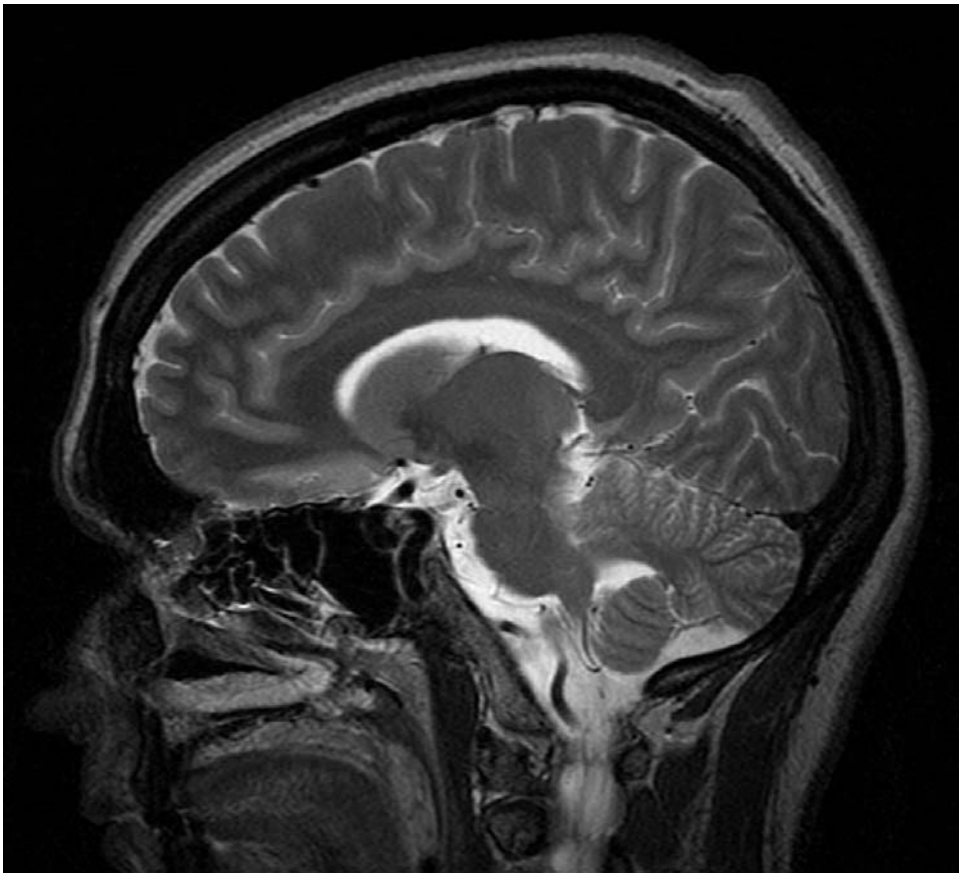

C44
C43
C45
C42a
C67
C5
C31
C94
C77
SC2a
SC14e
SC5
C1
SC14l
C74
C74a
C3
SC3
C41
H5b
C89
C9
H1
C79
H5a
CE2a
C81
CE2b
TC22
CE2c
CE1i
CE2d
CE2e

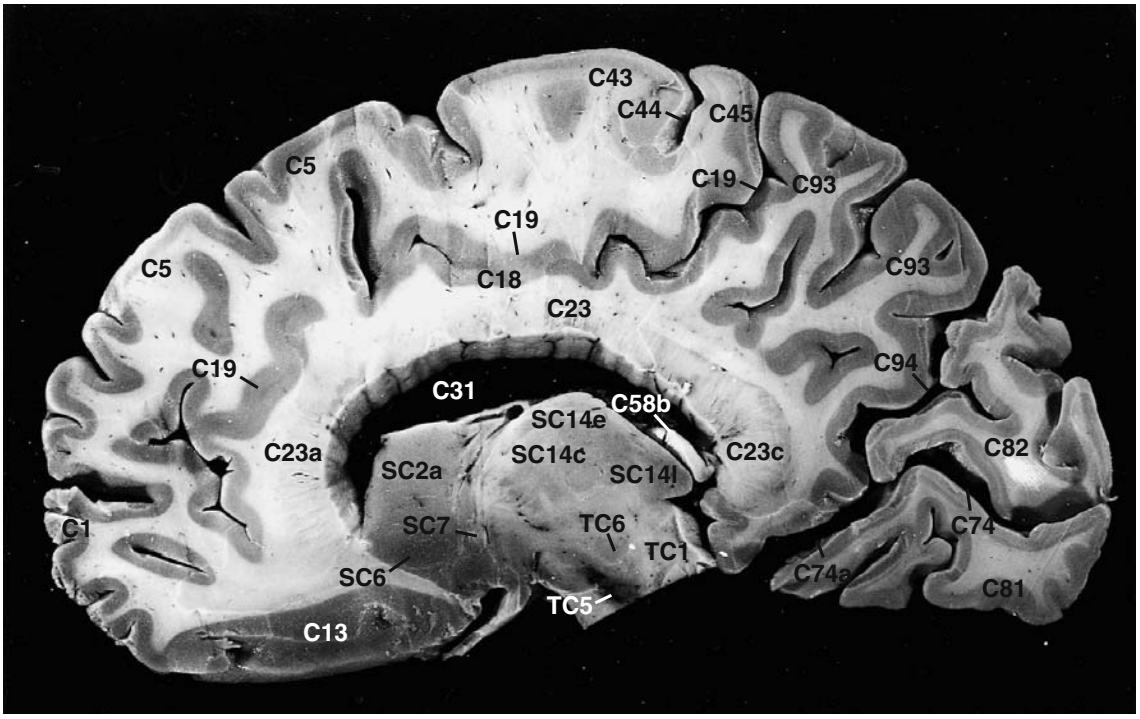


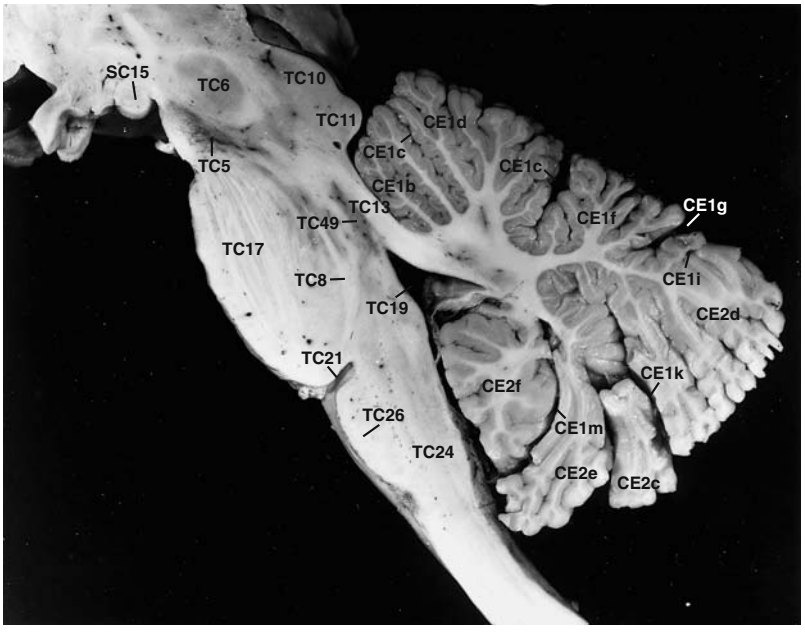

C45
C5
C43
C42a
C44
C67
C94
C1
C31
C77
C1
SC2a
SC14e
C74
SC5a
SC5c
SC14l
C74b
C89
SC7
SC4b
SC14f
C3
SC14k
H5b
SC3
SC4a
C81
C79
C9
H1
C28
H5a

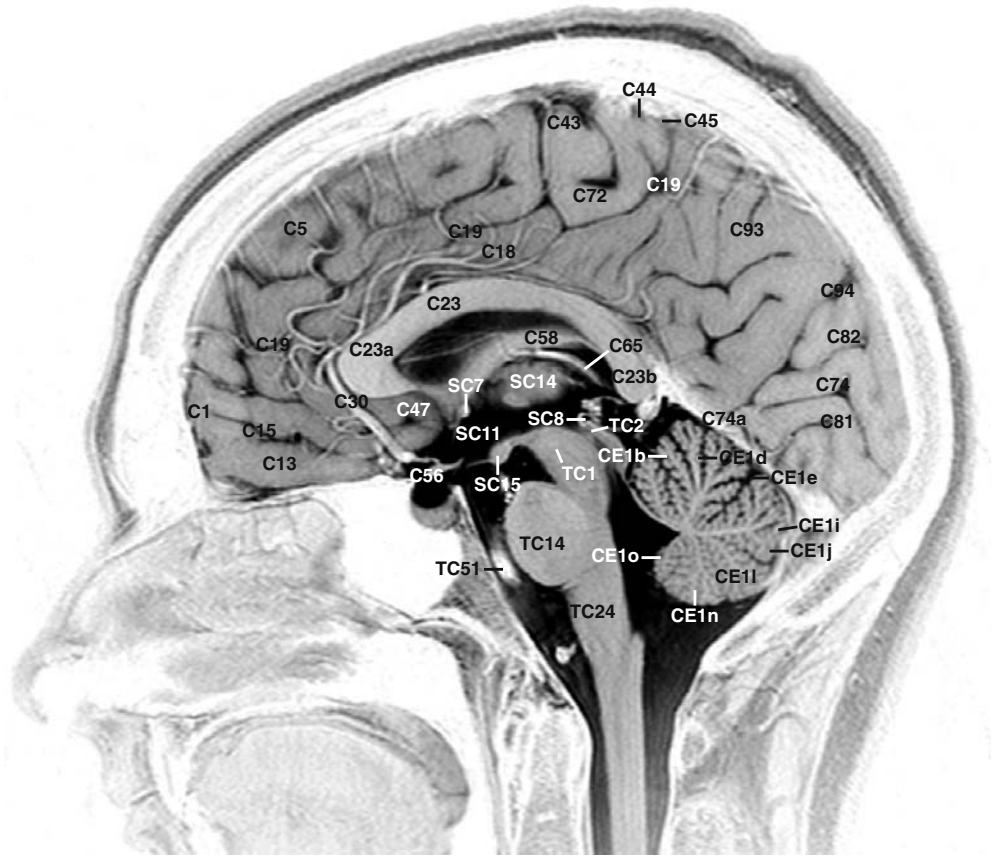
SC14l
SC14k
TC1
CE2a
CE1a
TC14
CE2b
CE2c
CE2g
CE1i
CE2e
CE1k
CE2d
TC24

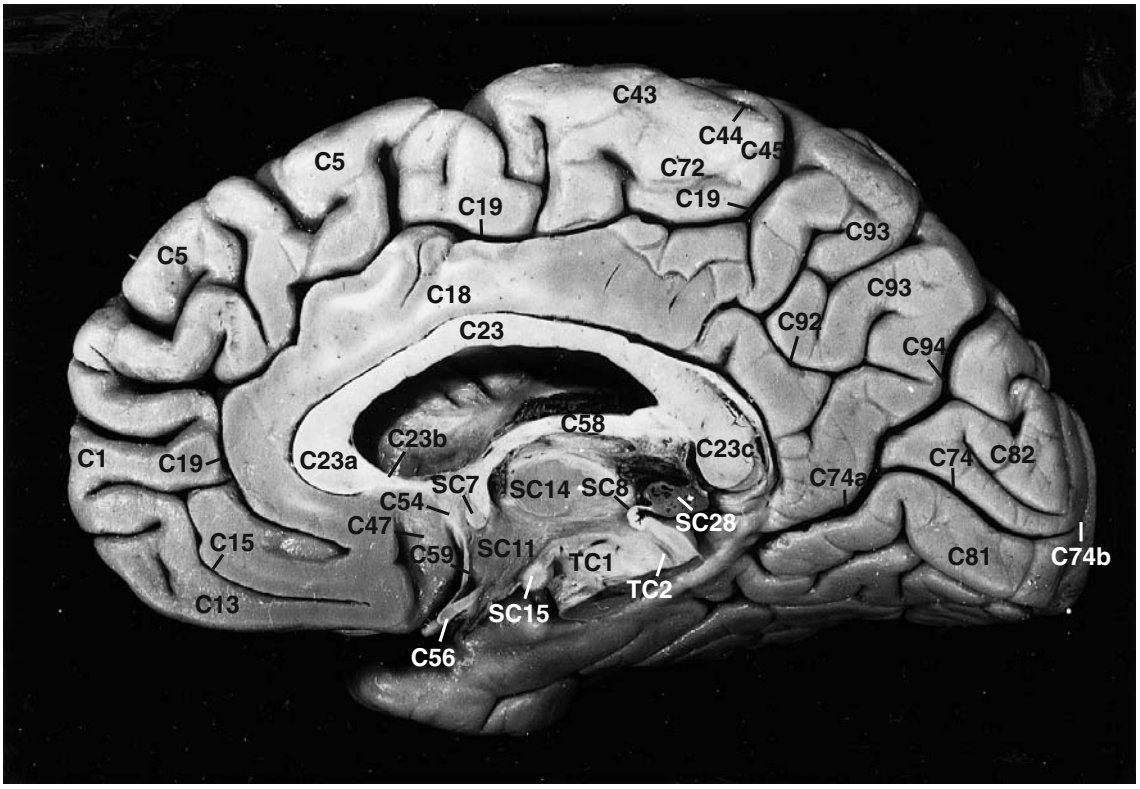

C43
C44
C45
C5
C19
C93
C18
C19
C94
C23
C31
C82
C1
C23a
SC2a
C23c
SC14c
SC14l
C74a
C74
SC6
TC1
CE1a
C13
C81
CE2b
CE2c
TC14
CE1i
CE2d
TC24
CE2e
CE2f

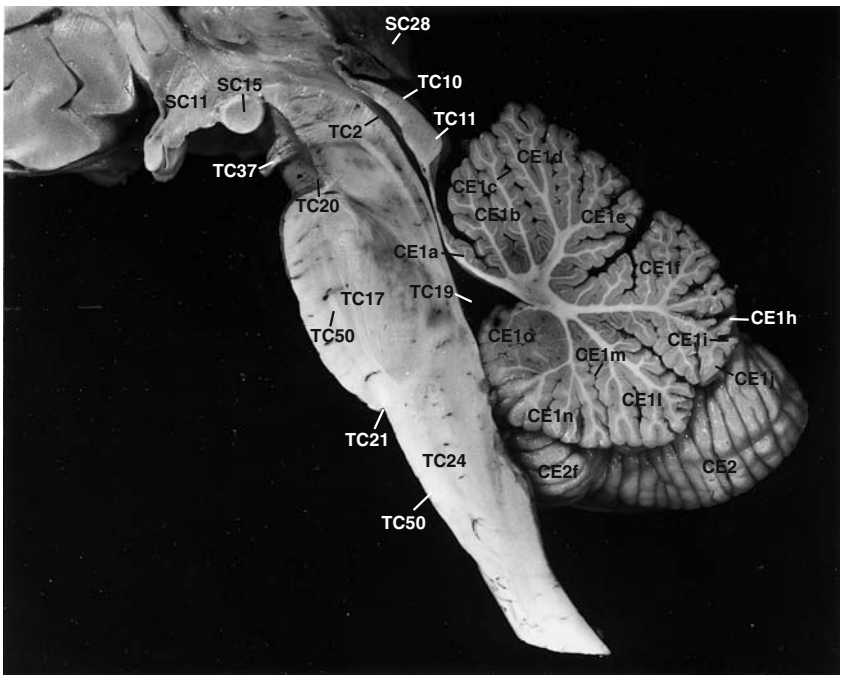



C43
C44
C45
C5
C19
C93
C19
C5
C18
C93
C23
C94
C19
C31
C58b
SC14e
C23a
SC14c
C23c
C82
SC2a
SC14l
C1
SC7
TC6
C74
TC1
SC6
C74a
C81
TC5
C13


SC15
TC6
TC10
TC11
CE1d
CE1c
TC5
CE1c
CE1b
TC13
CE1g
TC49
CE1f
TC17
CE1i
TC8
TC19
CE2d
TC21
CE1k
CE2f
TC26
CE1m
TC24
CE2e
CE2c


C44
C43
C45
C72
C19
C5
C19
C93
C18
C94
C23
C58
C65
C82
C19
C23a
C23b
C74
SC7
SC14
C30
C47
C74a
C81
C1
SC8
TC2
C15
SC11
CE1b
CE1d
C13
TC1
C56
SC15
CE1e
CE1i
TC14
CE1j
CE1o
TC51
CE1l
TC24
CE1n


C43
C44
C45
C5
C72
C19
C19
C93
C5
C18
C93
C23
C92
C94
C58
C23b
C23c
C1
C19
C23a
C74
C82
SC7
SC14
SC8
C74a
C54
SC28
C47
C15
C59
SC11
TC1
C81
C74b
TC2
C13
SC15
C56


SC28
SC15
TC10
SC11
TC2
TC11
CE1d
TC37
CE1c
TC20
CE1b
CE1e
CE1a
CE1f
TC17
TC19
CE1h
TC50
CE1g
CE1i
CE1m
CE1j
CE1l
CE1n
TC21
TC24
CE2f
CE2
TC50

FUNCTIONAL ATLAS

FUNCTIONAL STUDY OF THE BRAIN WITH MRI

Introduced in 1992 and continuously improved since, functional magnetic resonance imaging (fMRI) has rapidly become the most widely used approach to the study of human brain function by virtue of its sensitivity to cerebral functional phenomena and of its lack of biological invasiveness, resulting in unprecedented and unparalleled flexibility of use.

fMRI is based on a simple phenomenon, the variation of the MRI signal in relation to neuronal activity. This phenomenon, recognized in the early 1990s, depends mainly on blood oxygenation; its rationale is based on the much earlier observation by Pauling [1] that a change in the oxygenation of haemoglobin resulted in a change in its magnetic properties.

In 1990, Ogawa et al. [2] reported that MRI was sufficiently sensitive to show changes in the magnetic properties of haemoglobin, and that blood oxygenation level-dependent (BOLD) signal changes could be detected in vivo. In 1991, Turner et al. [3] observed a similar effect during experimental anoxia not only in the larger vessels, but also, interestingly, in brain tissue itself. Based on the known changes in brain oxygen content that accompany neuronal activity [4, 5], it was predicted that a technique based on the BOLD effect could be used to study brain function in vivo. It took a few months for three groups of researchers to demonstrate, in 1992, the applicability of BOLD-based fMRI to the study of human brain [6–8]. The correspondence between fMRI signal and neuronal activity has recently been proved also in animal systems [9].

One of the most valuable features of fMRI compared with the other methods of functional neuroimaging is its spatial resolution, which allows to obtain more precise and better localized information than nuclear medicine-based methods (Single Photon Emission Tomography – SPECT, and Positron Emission Tomography – PET). The co-recording of functional data and high-resolution anatomical scans, which can be obtained in the same subject in a single session, is another valuable application of fMRI to the study of brain functional anatomy.

Since its introduction, high spatial resolution coupled with the precise spatial correspondence of functional information with the anatomical images obtained in the same experimental session has made fMRI the ideal method to study the functional anatomy of the brain.

Given that in fMRI high spatial resolution is associated with a reduced signal-to-noise ratio, a key strategy to improve spatial and temporal resolution is to offset the loss of signal using high magnetic field intensities. This has stimulated the diffusion of high-field units for human studies throughout the world, with very high-field machines (up to 8 Tesla) operating at a small number of institutions and a larger number of high-field imagers (3-4 Tesla) installed in many countries.

The availability of high-field fMRI units has greatly stimulated the application of this method to the detailed study of brain functional anatomy. Many areas of research in neuroscience have benefited from the advantages afforded by this new research tool. Among the many achievements of fMRI in neuroscience research, its contribution to the clarification of the functional anatomy of sensory regions has been particularly significant [10, 11]. Its high spatial detail has allowed to provide a precise map of human visual areas [12], and even to approach the columnar organization of sensory processing in the visu-

al domain [13]. In the auditory system, the contribution of fMRI has been similarly outstanding. Use of specially tailored experimental study designs to avoid scanner noise interference [14] has allowed to identify several specialized areas in the auditory cortex, where information regarding the regular distribution of sound frequency in the auditory cortex [15], the movement of sound stimuli [16], and the processing of voice [17] and even of syntactic and lexical information [18] is selectively processed.

The cooperative and convergent efforts of fMRI research and the newest and most powerful techniques of data processing have allowed to go beyond the study of the brain's macroscopic functional anatomy, enabling perceptive and innovative interpretations of regional brain physiology. In a recent study [19], neural activity in the auditory cortex was sampled at high temporal resolution without interference from the scanner's noise. The application of a novel technique of temporal decomposition of different neural behaviours has allowed to identify the presence of two independent neural activities, indicating the coexistence of a sustained and a transient response to a single continuous sound stimulus. These probably represent fundamental operational modes of the auditory cortex, whose differentiation is crucial for this system to accomplish correct processing of sounds and voice noise.

A powerful innovation introduced by the neurophysiological applications of fMRI consists in the possibility of recognizing the presence of different neural behaviours and at the same time of localizing their spatial source in fine anatomical detail. In this study of the auditory cortex [19], the two different activities were distributed in space with astonishing precision, corresponding respectively to Heschl's gyrus (the sustained activity) and to planum temporale and the pole of the temporal lobe (the transient activity).

However, the prospects of neurophysiological fMRI go far beyond its application to auditory processing, and will probably permit a much more exhaustive and detailed comprehension of the brain's functional anatomy.

Since its introduction, the development of fMRI has proceeded at a very fast pace stimulated by research in many different disciplines, whose most advanced results have found applications in functional neuroimaging. Particularly important has been the convergence and integration of the achievements of three fields of research: technology, physics and data processing. A crucial impulse has come from advances in the technology of magnetic field gradients, which have provided more powerful and faster gradients permitting to enhance the temporal resolution of functional time-series and to improve sensibly spatial resolution and image quality, especially in combination with high-intensity magnetic fields [20]. A second, decisive contribution has come from MRI physics, whose advances have yielded many new sequences to improve the results of BOLD-based fMRI, and ever new solutions to overcome its shortcomings [21]. It is worth mentioning again the quantum leap that has permitted to improve the spatial resolution of fMRI so much as to allow to explore the functional areas and investigate information processing at the level of the single columnar processors. These decisive advances have been enabled by the decomposition of BOLD temporal dynamics and by use of an "early negative" component, which reflects much more localized oxygenation phenomena than those generating the conventional positive BOLD component [13]. A third pivotal contribution has come from astonishing improvements in data processing providing both statistical rigour and high flexibility in extracting functional information from fMRI time-series. New processing functions have allowed to overcome the problem of minor head movements during fMRI investigations, to correct the data for physiological phenomena and for scanner instability, and have provided new tools for the anatomical representation of functional information. New and powerful data processing techniques have allowed to obtain high-resolution 3D surface representations of cerebral

cortex by segmenting the conventional MRI data and to subject them to sophisticated mathematical procedures of "unfolding". The gyral structure of brain cortex, which probably responds to evolutionary and ecological requirements, poses severe problems to the fine interpretation of neural processes. For instance, it is impossible to understand correctly the somatotopical organization of cortical areas: this is now much easier using the so-called inflated and flattened non-gyral derivatives of brain cortex. A final example of the contribution from research in data processing is the recent progress in procedures permitting the non-inferential extraction of functional information from fMRI time series [22]. By avoiding use of inferential processes, researchers may find in the data something that they themselves do not know in advance, or something that they can imagine but are unable to translate precisely into a haemodynamic model, as already demonstrated [19]. It is easy to anticipate that the latter option, together with the many other advances in the research converging on fMRI, will in the near future open completely new and promising avenues of neuroscience research.

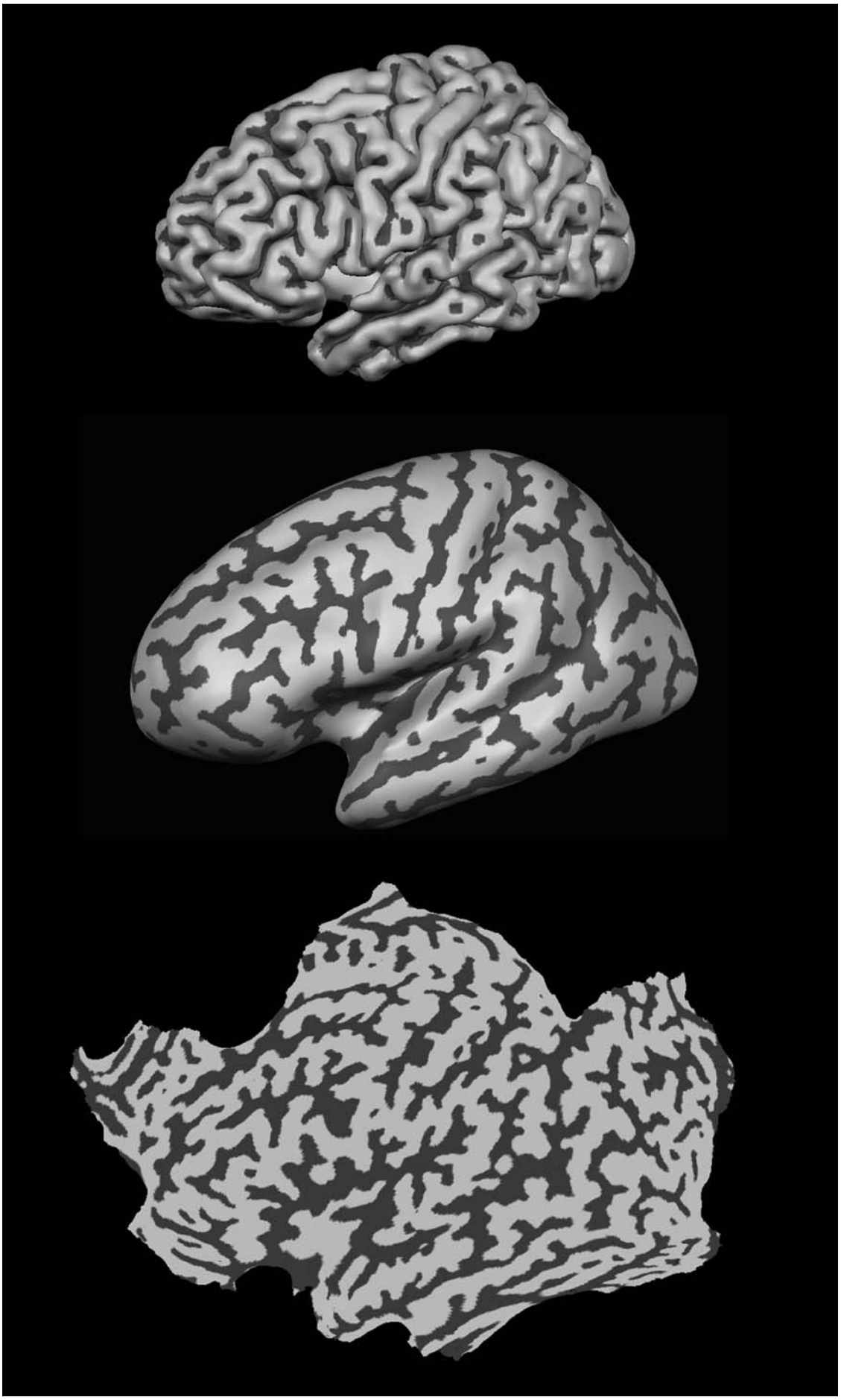
References

1. Pauling L, Coryell CD. The magnetic properties and structure of hemoglobin, oxyhemoglobin and carbonmonoxyhemoglobin. Proc Natl Acad Sci USA 1936;22:210-6.
2. Ogawa S, Lee TM, Nayak AS, Glynn P. Oxygenation-sensitive contrast in magnetic resonance image of rodent brain at high magnetic fields. Magn Reson Med 1990;14(1):68-78
3. Turner R, Le Bihan D, Moonen CT, Despres D, Frank J. Echo-planar time course MRI of cat brain oxygenation changes. Magn Reson Med 1991;22(1):159-66.
4. Raichle ME. Behind the scenes of functional brain imaging: a historical and physiological perspective. Proc Natl Acad Sci USA 1998;95(3):765-72.
5. Fox PT, Raichle ME. Focal physiological uncoupling of cerebral blood flow and oxidative metabolism during somatosensory stimulation in human subjects. Proc Natl Acad Sci USA 1986;83(4):1140-4.
6. Ogawa S, Tank D, Menon R, Ellermann JM, Kim SG, Merkle H, Ugurbil K. Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proc Natl Acad Sci USA 1992;89(13):5951-5.
7. Kwong KK, Belliveau JW, Chesler DA, Goldberg IE, Weisskoff RM, Poncelet BP, Kennedy DN, Hoppel BE, Cohen MS, Turner R, Cheng H-M, Brady TJ, Rosen BR. Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. Proc Natl Acad Sci USA 1992;89(12):5675-9.
8. Bandettini PA, Wong EC, Hinks RS, Tikofsky RS, Hyde JS. Time course EPI of human brain function during task activation. Magn Reson Med 1992;25(2):390-7.
9. Logothetis NK, Pauls J, Augath M, Trinath T, Oeltermann A. Neurophysiological investigation of the basis of the fMRI signal. Nature 2001;412(6843):150-7.
10. Polonara G, Fabri M, Manzoni T, Salvolini U. Localization of the first and second somatosensory areas in the human cerebral cortex with functional MR imaging. AJNR Am J Neuroradiol 1999;20(2):199-205.
11. Fabri M, Polonara G, Quattrini A, Salvolini U, Del Pesce M, Manzoni T. Role of the corpus callosum in the somatosensory activation of the ipsilateral cerebral cortex: an fMRI study of callosotomized patients. Eur J Neurosci 1999 Nov;11(11):3983-94. 12. Sereno MI, Dale AM, Reppas JB, Kwong KK, Belliveau JW, Brady TJ, Rosen BR, Tootell RB. Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. Science 1995;268(5212):889-93.
13. Kim DS, Duong TQ, Kim SG. High-resolution mapping of iso-orientation columns by fMRI. Nat Neurosci. 2000;3(2):164-9
14. Yang Y, Engelien A, Engelien W, Xu S, Stern E, Silbersweig DA. A silent event-related functional MRI technique for brain activation studies without interference of scanner acoustic noise. Magn Reson Med 2000;43(2):185-190
15. Wessinger CM, Buonocore MH, Kussmaul CL, Mangun GR: Tonotopy in human auditory cortex examined with functional magnetic resonance imaging. Hum Brain Mapp 1997;5(1):18-25.
16. Griffiths TD, Rees A, Witton C, Shakir RA, Henning GB, Green GG: Evidence for a sound movement area in the human cerebral cortex. Nature 1996;383(6599):425-427.
17. Belin P, Zatorre RJ, Lafaille P, Ahad P, Pike B: Voice-selective areas in human auditory cortex. Nature 2000;403(6767):309-312.
18. Friederici AD, Meyer M, von Cramon DY: Auditory language comprehension: an event- related fMRI study on the processing of syntactic and lexical information. Brain Lang 2000;75(3):289-300.
19. Seifritz E, Esposito F, Hennel F, Mustovic H, Neuhoff JG, Bilecen D, Tedeschi G, Scheffler K, Di Salle F. Spatiotemporal pattern of neural processing in the human auditory cortex . Science 2002;297(5587):1706-8.
20. Kim SG, Ugurbil K. High-resolution functional magnetic resonance imaging of the animal brain. Methods 2003;30(1):28-41.
21. Kim SG and Ogawa S. Insights into new techniques for high resolution functional MRI. Curr Opin Neurobiol 2002;12(5):607-615.
22. McKeown MJ, Makeig S, Brown GG, Jung T-P, Kindermann SS, Bell AJ, Sejnowski TJ. Analysis of fMRI data by blind separation into indipendent spatial components. Hum Brain Mapp 1998;6(3):160-188.

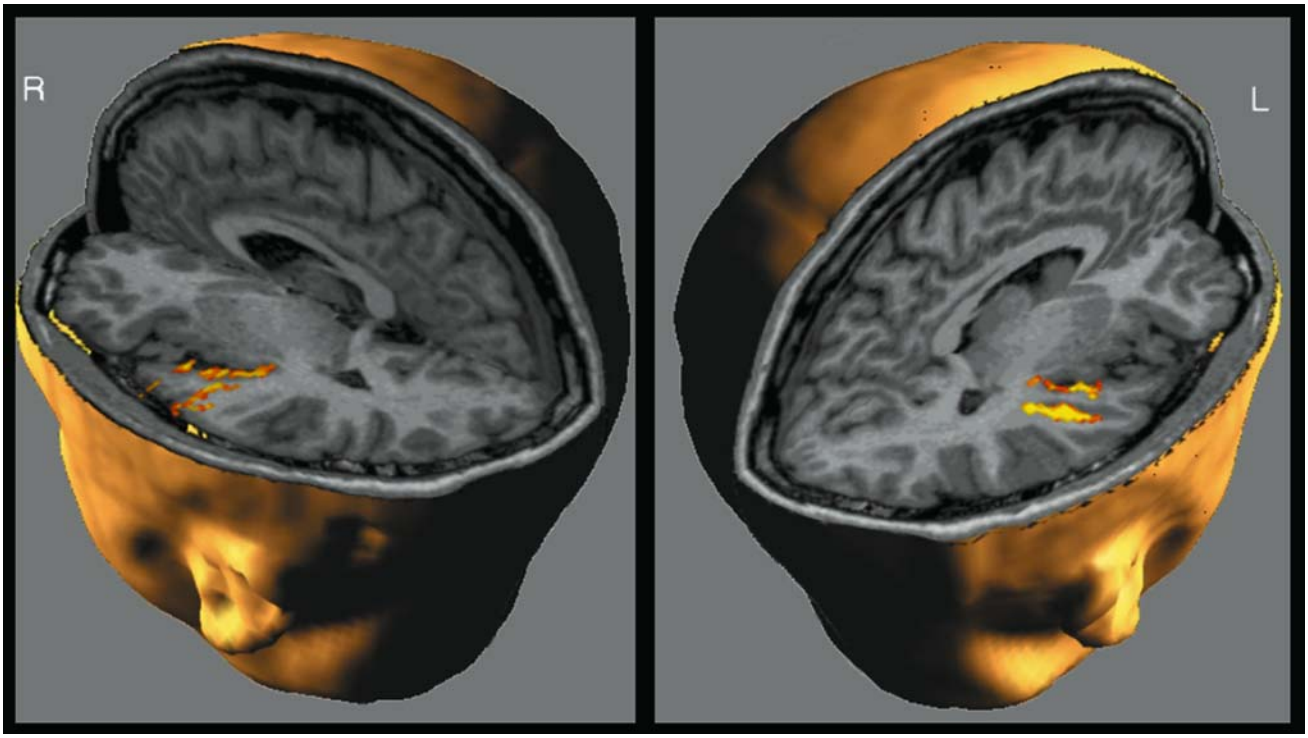
fMRI

Morphing procedures of the brain surface used to improve functional data representation

In order to improve the representation of functional data on the cortical surface, some morphing procedures are often applied on the anatomical surfaces. These procedures have to be topologically correct, so as to avoid modifying the original spatial relationships among cortical structures. The main morphing procedures are inflation and flattening. The effect of the former is to let the depth of cortical sulci grow towards the most external surface of cortical gyri. This way the brain loses its naturally folded appearance, and allows a better inspection of neural activity taking place inside the sulci. The procedure called flattening operates on previously inflated surfaces, producing appropriate cuts along the mesial surface of each hemisphere. These cuts separate different regions in the mesial surface of the hemisphere, which are then unfolded to the external surface by applying "unfolding vectors" on each region. The result of the flattening procedure is to produce a planar representation of each hemisphere, which allows a complete synoptical examination of brain cortex. The folded, inflated and flattened images presented here are produced on the data of the Montreal Neurological Institute (MNI) standard brain through the application of Brain Voyager (www.brainvoyager.com). The same software was used to produce the statistical maps and to process the anatomical data in the following figures.

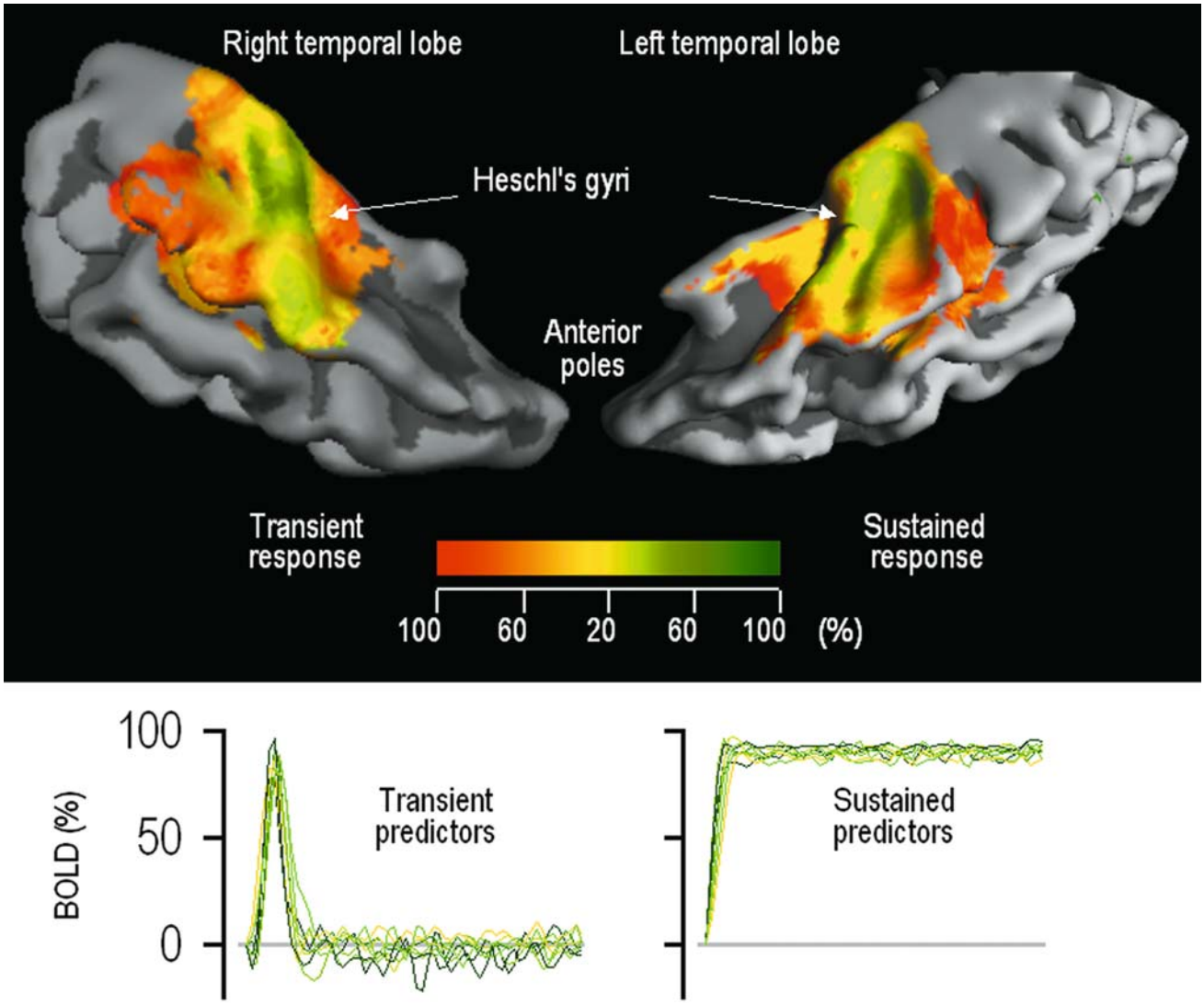


fMRI of the auditory system



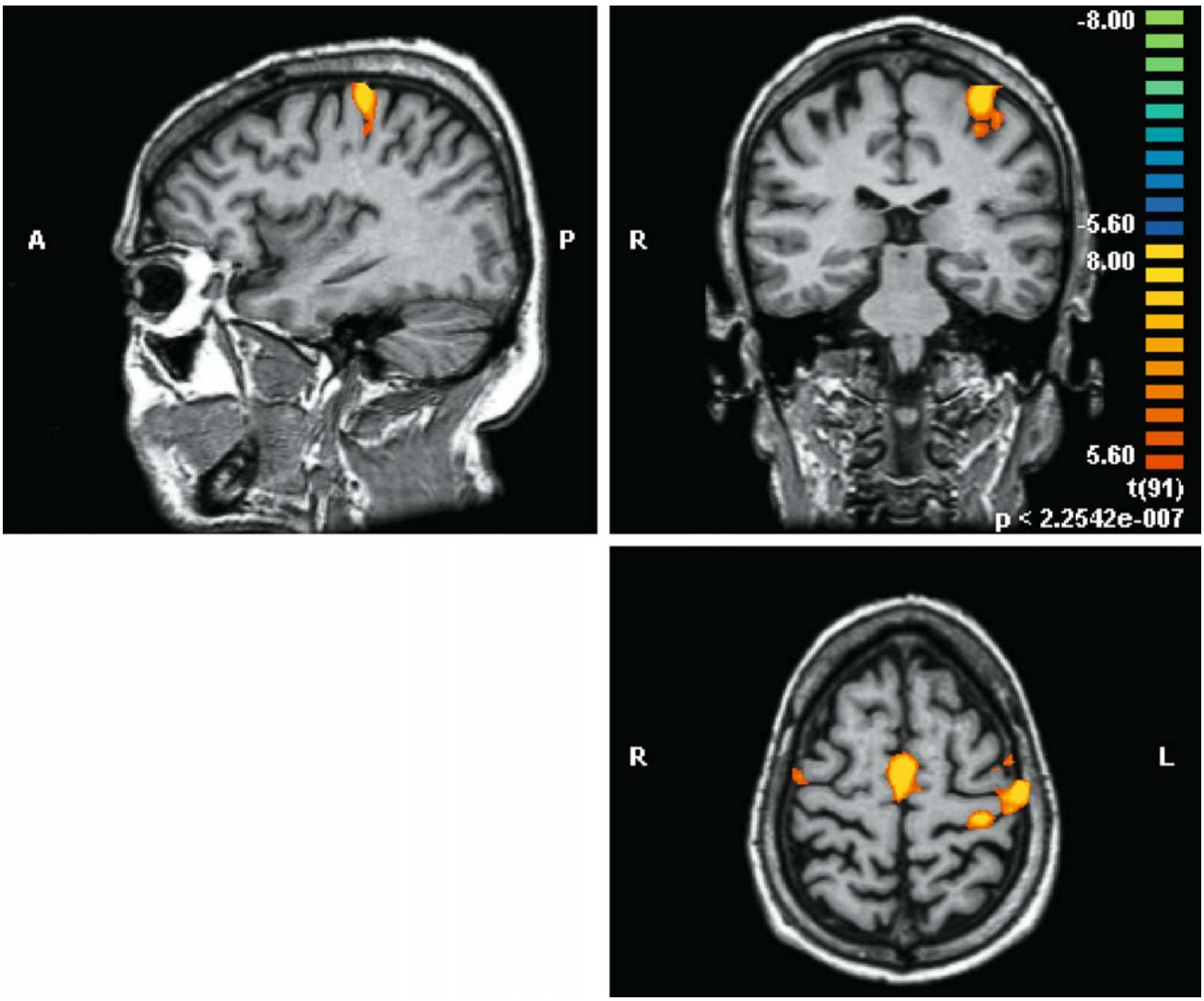
The stimulus used is a 1000 Hz pulsed (5 Hz) tone, binaurally perceived by the volunteer in a silent environment through a clustered acquisition technique. Neural activity is represented as a colour-coded map, thresholded at a significance level of $p<0.05$ corrected for multiple comparisons, and projected onto a 3D anatomical volume of the head and brain. The area of activation, where yellow pixels indicate a higher statistical significance than red pixels, includes bilaterally the transverse gyri of temporal lobe and extends on the right side to the planum polare.

Separation of different neural dynamics in the auditory cortex

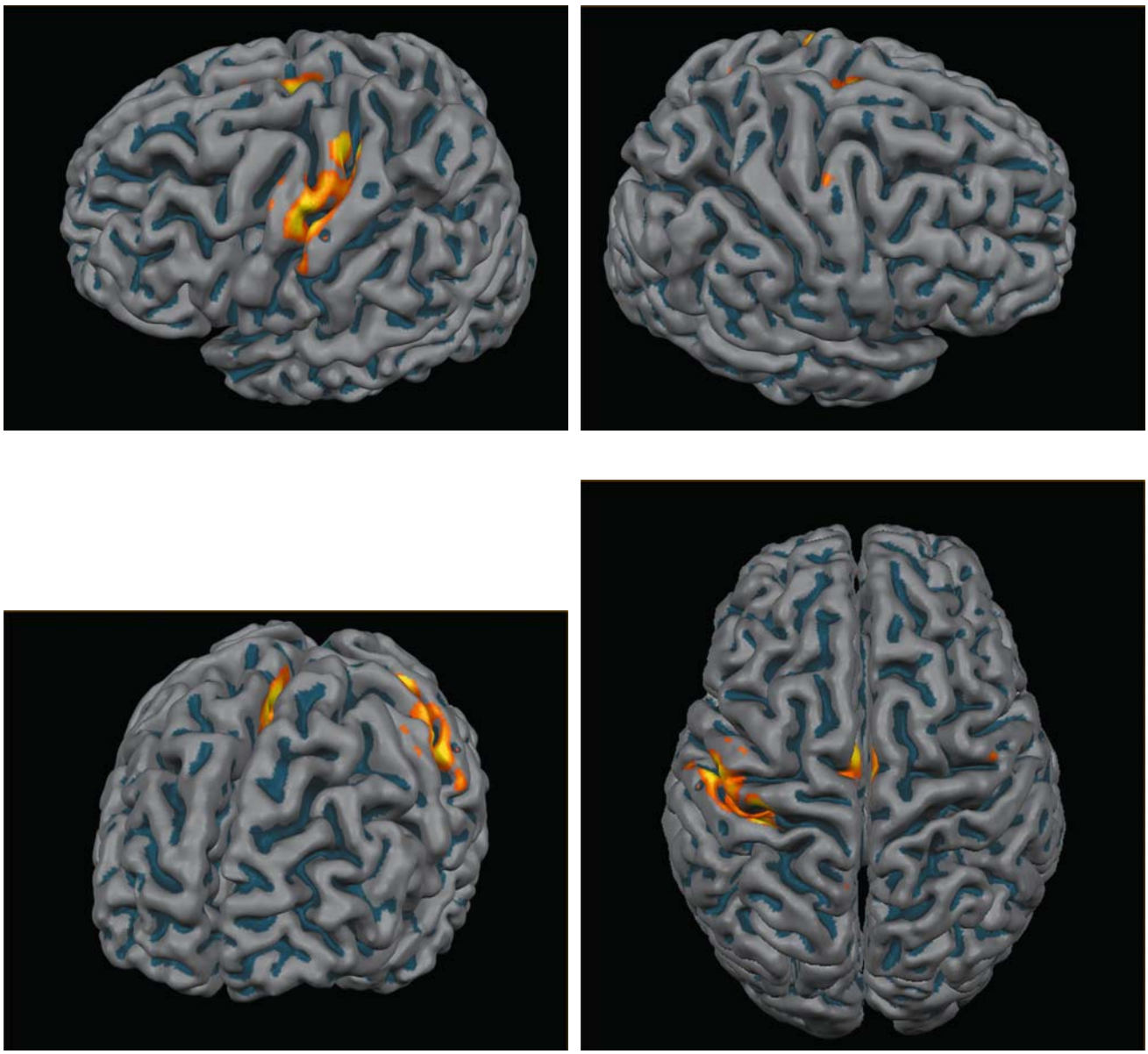


Two different operational modes of the auditory cortex have been extracted with a non-inferential procedure using Independent Component Analysis. This mode separates a transient and a sustained response to a continuous auditory stimulation and their spatial distribution follows exactly the distinction between "core" (Heschl) and "belt" (planum temporale and planum polare) in the auditory region. Reprinted with permission from: Seifritz E. et al.: Spatiotemporal pattern of neural processing in the human auditory cortex. Science. 2002 Sep 6;297(5587):1706-8. Copyright 2002, American Association for the Advancement of Science.

fMRI of the motor function

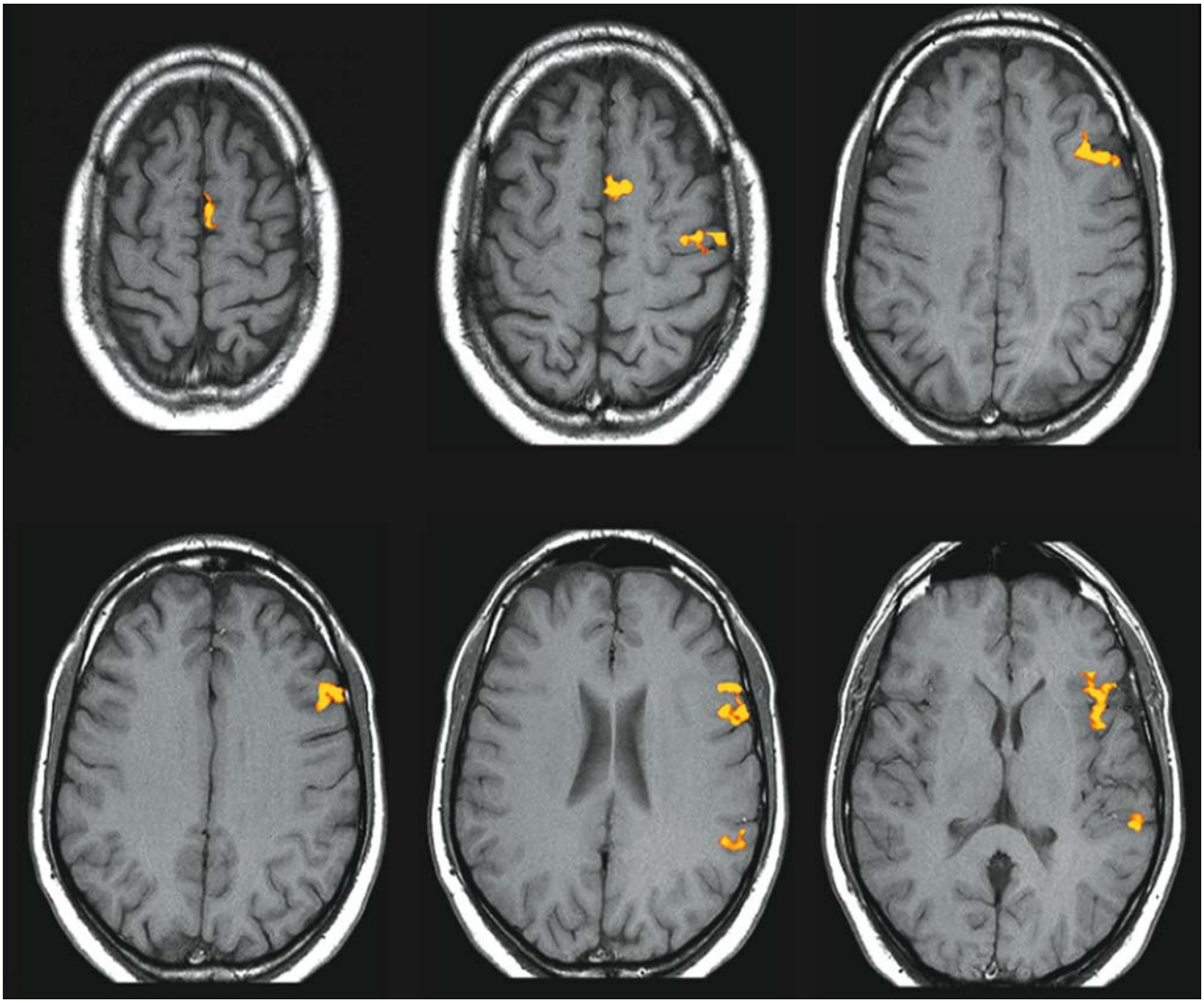


The volunteer is asked to move his right index finger with minimal strength at an externally paced frequency of 0.5 Hz. A colour-coded statistical map of neural activity is thresholded at $p < 0.05$, corrected for multiple comparisons, and superimposed to the tri-planar (Sagittal, Coronal and Axial planes) anatomy of the volunteer (this page) and to surface representations of cortical anatomy (next page).

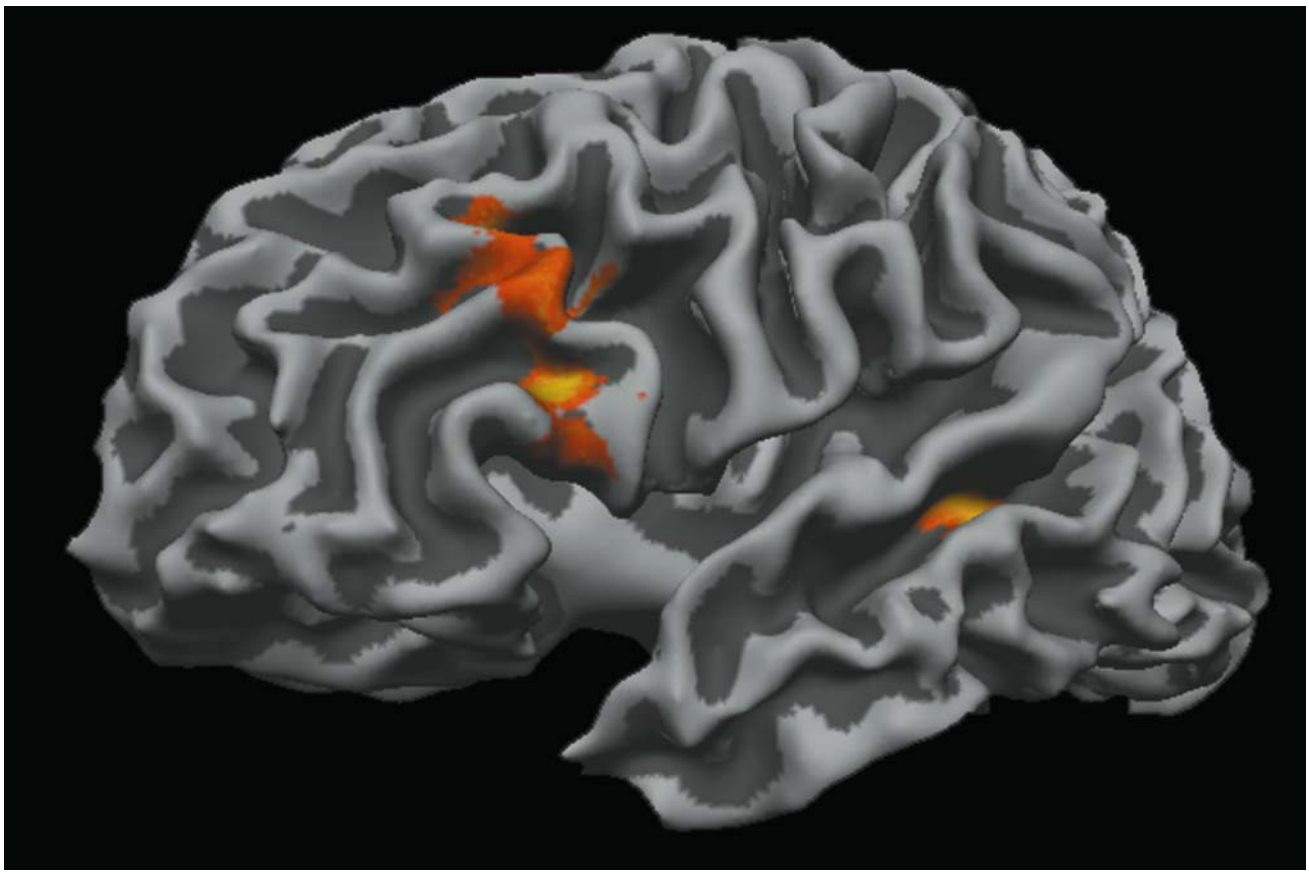


The large focus of activation corresponds to the Rolandic region, and includes both the pre and shown in the image post rolandic cortex.
A second focus of activity is evident on the mesial surface of frontal lobe in both the hemispheres, corresponding to the supplementary motor area.

fMRI of language production

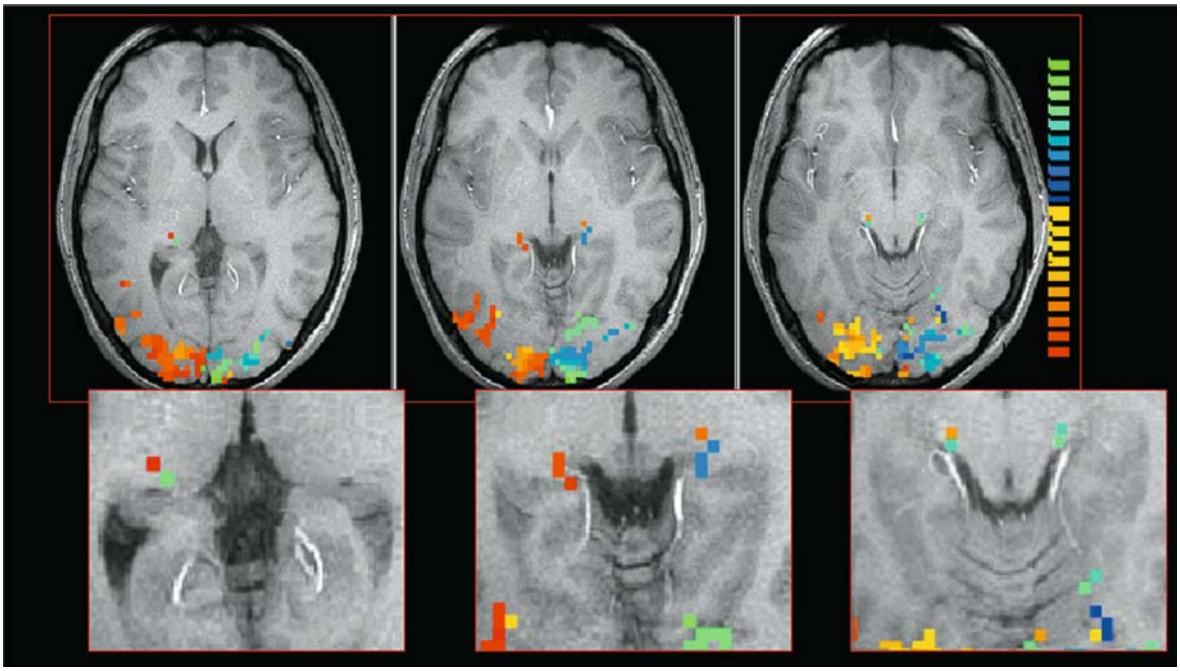


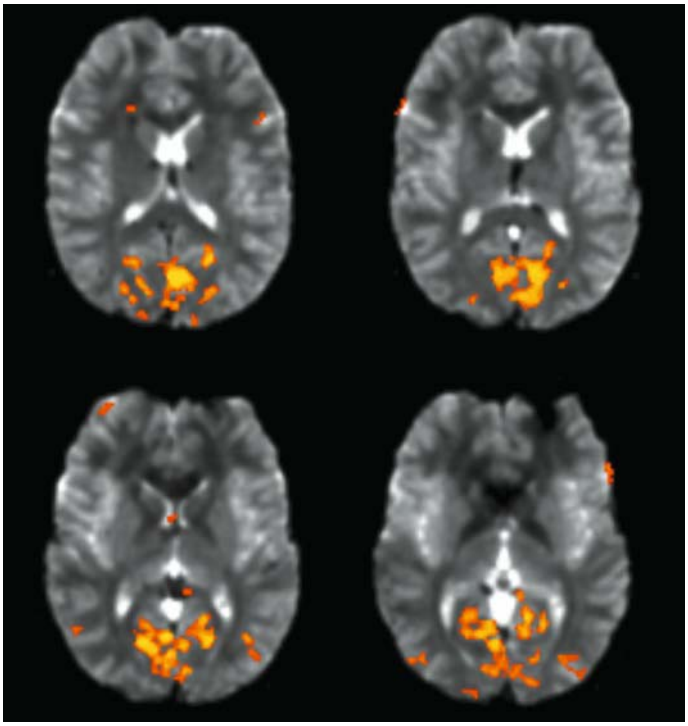
The volunteer is asked to think of words beginning with a specified letter, at a self-paced frequency to be kept as high as possible. A colour-coded statistical map of neural activity is thresholded at $p < 0.05$, corrected for multiple comparisons, and superimposed to axial slices (this page) and to the surface representations (next page) of the cortical anatomy of the volunteer. Four main foci



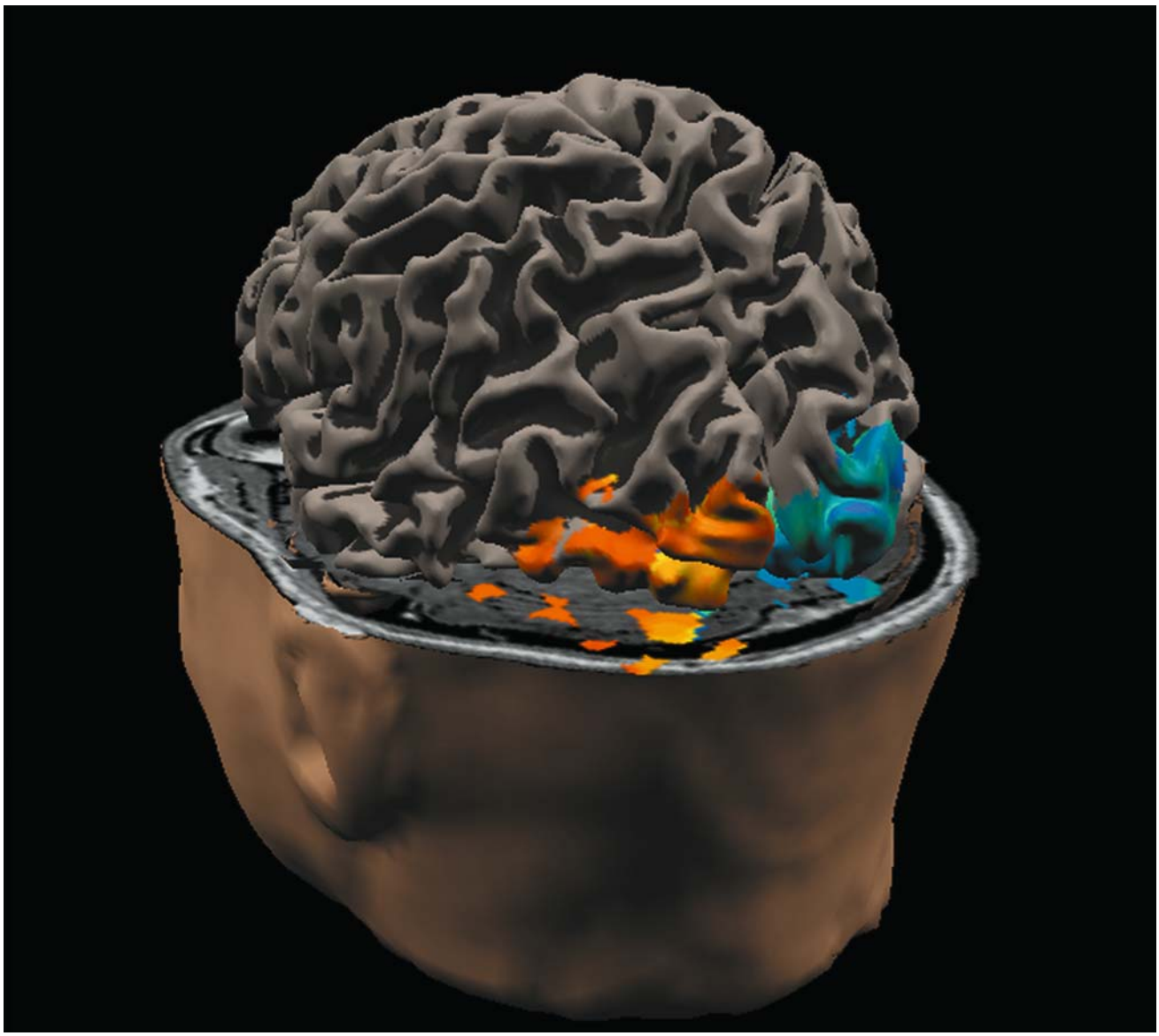
of activity are evident, localised in the left frontal operculum (Broca's region), the foot of the second frontal gyrus of the left hemisphere (the Dorso-Lateral Pre-Frontal Cortex – DLPFC), the left temporal lobe (Wernicke's region), and the left mesial surface of the frontal lobe, corresponding to the supplementary motor region.

fMRI of visual perception



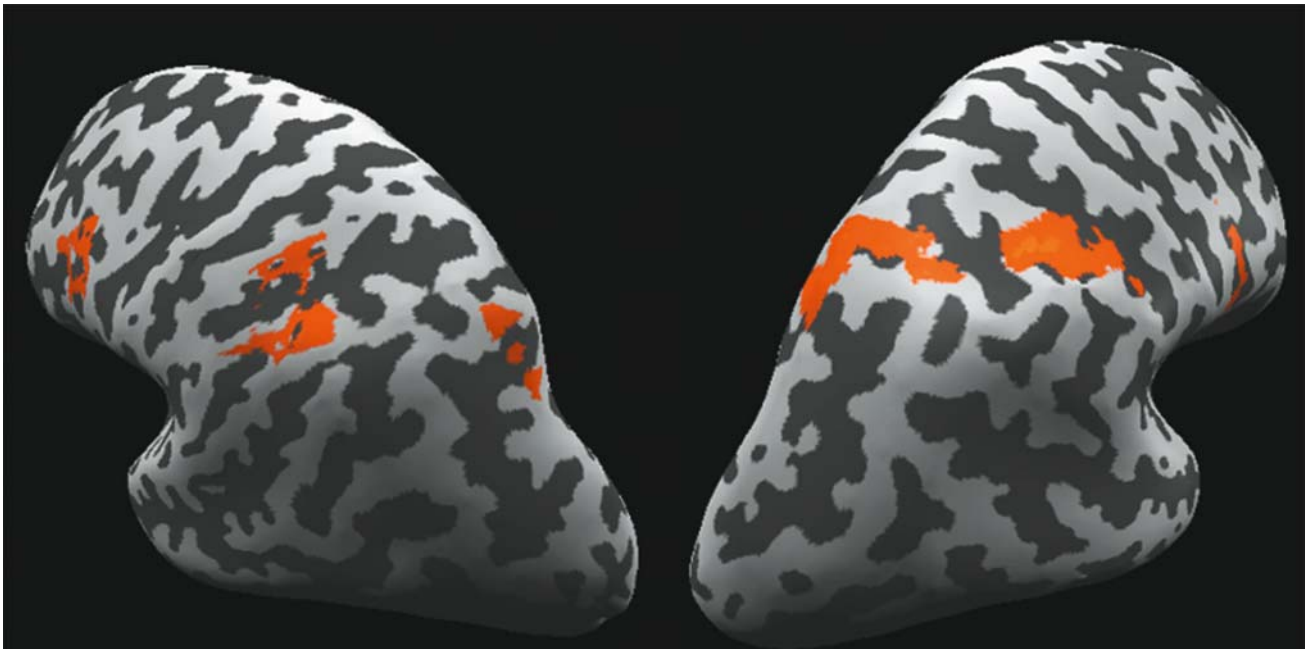


The volunteer is presented with a "retinotopical" stimulus, consisting of a rotating circular sector that is scanned continuously. A colour-coded statistical map of neural activity is thresholded at $p < 0.05$, corrected for multiple comparisons, and superimposed (this page) to axial Echo-Planar (EPI) and high-resolution morphological T1 images, and (next page) to the surface anatomy of the volunteer. The colour code represents statistical significance (on the



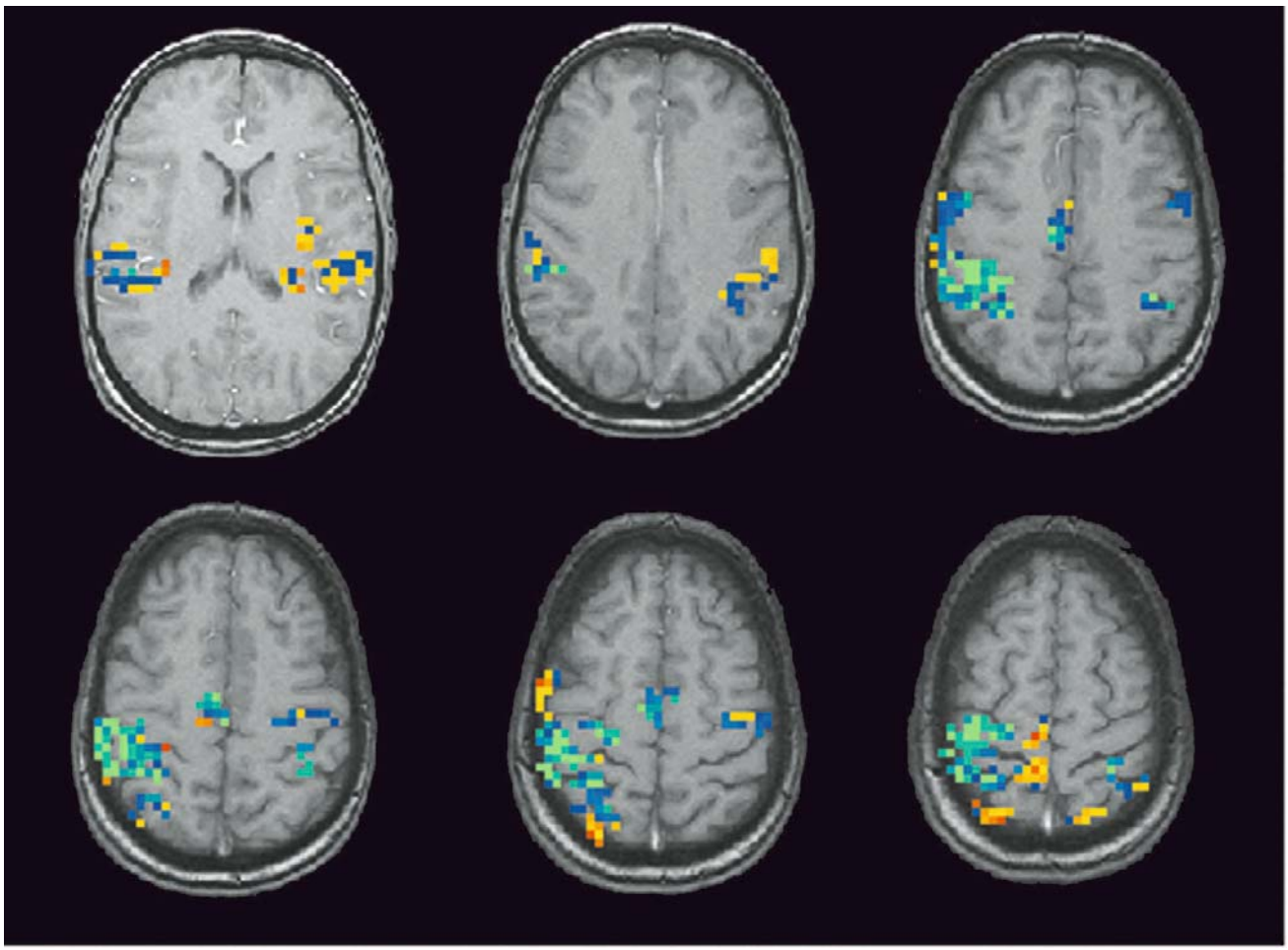
EPI images) and time (on the T1 images and on the surface anatomy). In the latter, each colour in the map corresponds to the specific position of the stimulus in the retinal visual field, so allowing to appreciate the retinotopical organization of the calcarine region. In the 2D T1w images the brainstem and thalamus are enlarged to show activation in the geniculate region.

fMRI of visual imagery



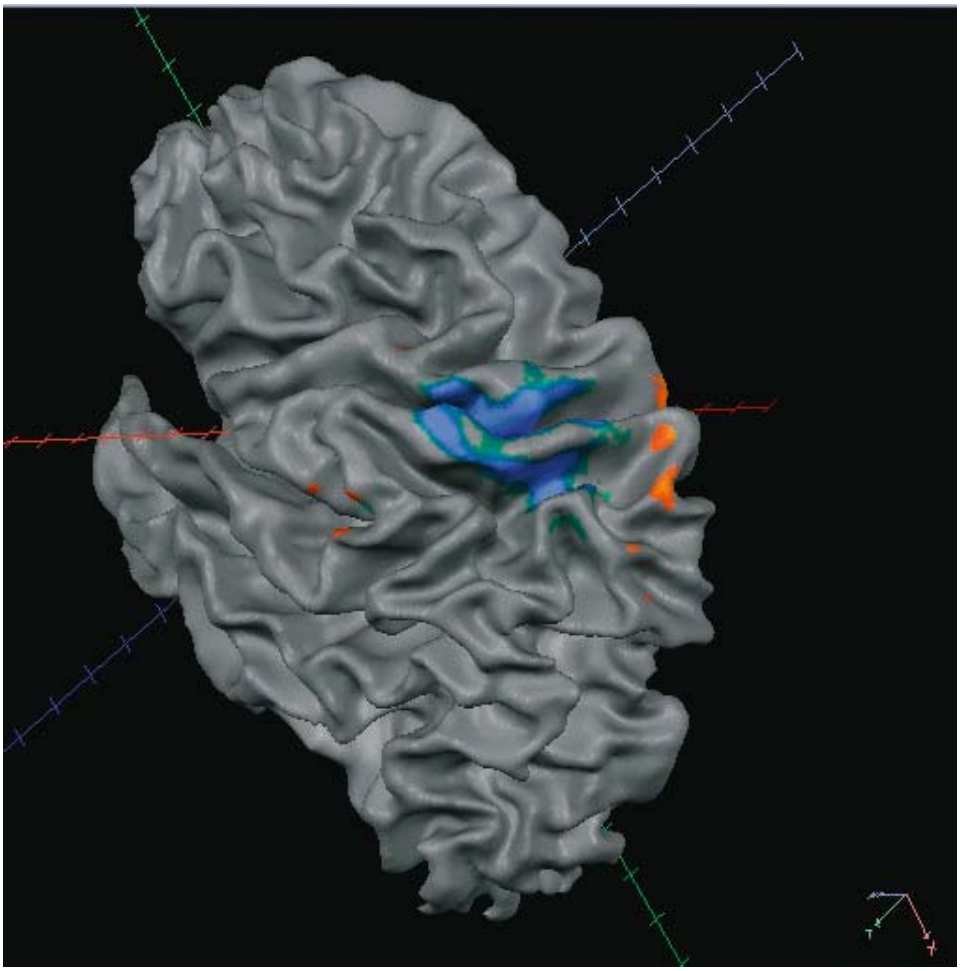
The volunteer is asked to imagine two clock faces, oriented as described verbally by the examiner to compare the angles formed by the hands on the two faces and to indicate the greater one. As a control condition, from the same two verbal indications the volunteer has to indicate the numerically greater one. A colour-coded statistical map of neural activity is thresholded at $p < 0.05$, corrected for multiple comparisons, and superimposed to a surface representations of the cortical anatomy after a process of "inflation" which lets the surface grow smoothly into the grey matter. Sulci are indicated as darker shades of grey. The activity is localized in the intraparietal sulcus.

fMRI of the somatosensory system

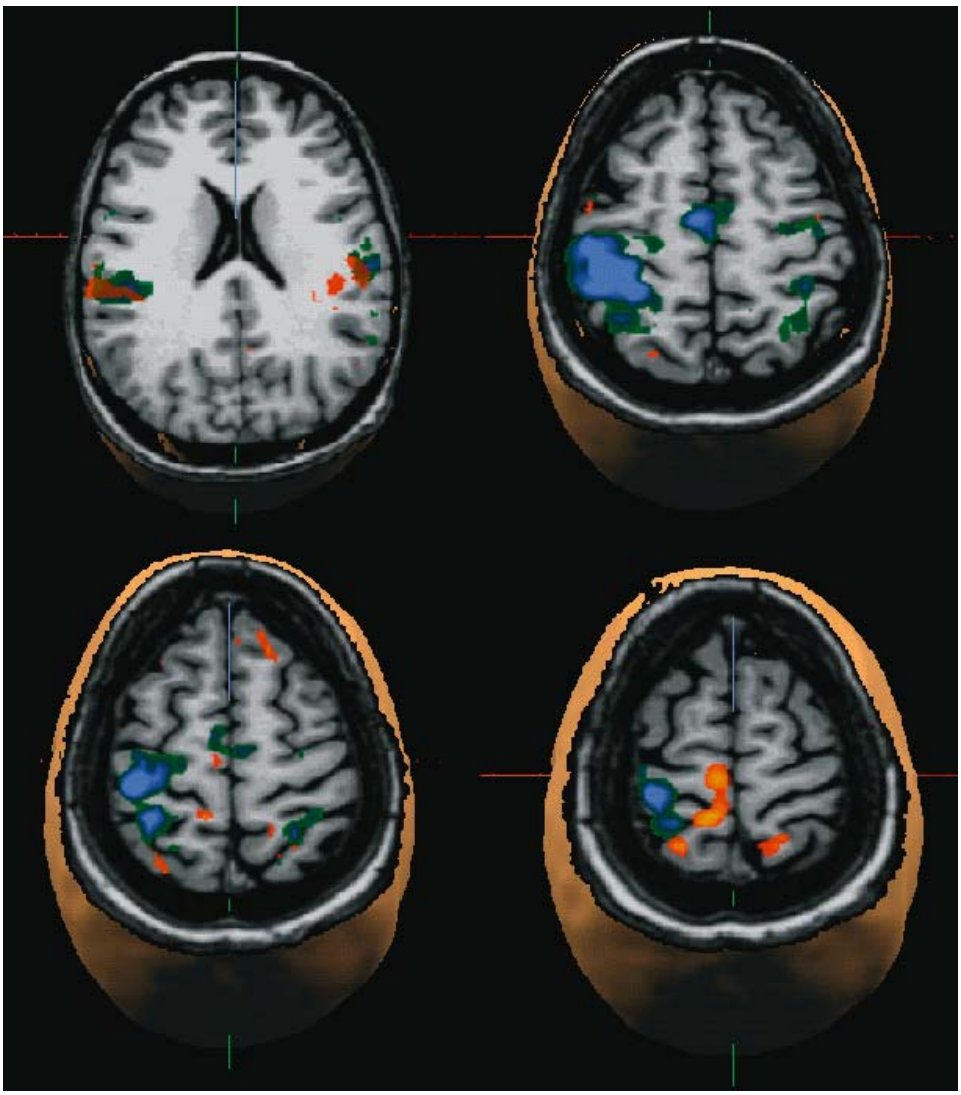


Cortical activation obtained during alternating tactile stimulation of the left foot and hand. A colour-coded statistical map of neural activity is superimposed to T1 weighted axial slices of the volunteer. Yellow and red pixels correspond to areas activated during tactile stimulation of the left foot, green and blue pixels to areas activated during stimulation of the left hand. The activity is mainly localized in the right anterior parietal cortex, in the posterior parietal cortex and in the parietal opercular cortex of both hemispheres. In the postcentral gyrus, areas corresponding to foot stimulation are located more medial than those activated by tactile stimulation of the left hand. Activation foci are also detectable in the frontal cortex. See also: Polonara G. et al.: Localization of the first and second somatosensory areas in the human cerebral cortex with functional MR imaging. AJNR 1999 20:199-205.

fMRI of the somatosensory system



Cortical activation obtained in a volunteer during alternating tactile stimulation of the left foot and hand. A colour-coded statistical map of neural activity is superimposed on axial sections obtained from a 3D anatomical volume of the head and brain (1) and on the surface of the brain (2). Yellow and red pixels correspond to areas activated during tactile stimulation of the left foot, green and blue pixels to those activated during stimulation of the left hand.



Activation is prevalently localized in the right anterior parietal, posterior parietal and parietal opercular cortices bilaterally. In the post-central gyrus, the areas activated by foot stimulation are more medial than those activated by tactile stimulation of the left hand. Activation foci are also detected in the frontal cortex.
See also: Polonara G. et al.(1999)